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Prepared by:

T. A. Fonstad, Ph.D., P.Eng. and Crystal Rinas, B.E.
Department of Agricultural and Bioresource Engineering
University of Saskatchewan

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ABSTRACT

This final report covers results of monitoring the groundwater near four earthen manure storages (EMS) in Saskatchewan over the period of 2001 to 2005. The storages consist of:

- a non-engineered pit constructed in sandy soils in 1984 and services a 200 sow farrow to finish swine barn,
- an engineered two-cell EMS constructed in clay soils that services a 600 sow farrow to finish swine barn,
- an engineered two-cell EMS constructed in a layered sandy till soils that services a 10,000 head hog finishing barn, and
- an engineered two-cell EMS constructed in till soils that services a 1200 sow farrow to finish swine barn.

The report is provided as four separate papers.

Paper No. 1, Chemistry of Stored Swine Manure: A Geochemical Approach, discusses the chemistry of samples taken from seven hog manure storages. The samples were filtered to 0.45 µm and analyzed for major ions, dissolved organic carbon, dissolved inorganic carbon and metals. This study indicated that ammonium nitrogen is the most abundant form of nitrogen and one of the most abundant ions in EMS effluent.

Paper No. 2, Design of a Groundwater Monitoring System for Earthen Manure Storages, discusses the design process, design and installation of the monitoring system used for monitoring the three new EMS. The system designed consisted of 24 piezometeric tips at 4 location and various depths within each cell of an EMS. Tips have
a pneumatic piezometer (or are standpipes), a thermocouple, a platinum redox probe, and two 3.2 mm diameter tubes. The report also cover sampling and data collection protocols used at the sites.

Paper No. 3, Long Term Monitoring Results from Three Earthen Manure Storages in Saskatchewan, discusses the results of sampling and data collection at the three EMS that have been monitored since their commissioning. Groundwater chemistry analysis results and water table changes with time are plotted over the site geographic cross sections. Seepage extends to depths of up to 1.5 m below the EMS and up to 10 m parallel to the toe of the inside slope of some of the EMS sites. The EMS that have the greatest extent of seepage have experienced liner damage in the past.

Paper No. 4, Characterization and Propagation of a Hog Manure Seepage Plume in a Sandy Saskatchewan Soil, discusses the characterization of the plume at the non-engineered EMS constructed in the sandy soils. A contaminate plume, indicated by elevated chloride concentrations, extends approximately 60 m south of the storage and approximately 6 m vertically downwards. This paper is the result of several projects including a portion of a Ph.D. thesis.

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INTRODUCTION

This final report covers results of monitoring the groundwater near four earthen manure storages (EMS) in Saskatchewan over the period of 2001 to 2005. The storages consist of:

- a non-engineered pit constructed in sandy soils in 1984 and services a 200 sow farrow to finish swine barn.
- an engineered two-cell EMS constructed in clay soils that services a 600 sow farrow to finish swine barn.
- an engineered two-cell EMS constructed in a layered sandy till soils that services a 10,000 head hog finishing barn, and
- an engineered two-cell EMS constructed in till soils that services a 1200 sow farrow to finish swine barn.

These sites were installed with monitoring equipment between 1994 and 1999 and initial groundwater and soil monitoring was conducted under other studies. This project covered groundwater sampling and analysis yearly from 2001 to 2005. Due to the amount of data generated, the plots provided in the report are for the 2001 (start) and 2005 (end) sampling dates. Groundwater chemistry analysis results and water table changes with time are plotted over the site geographic cross sections.

The report is provided as four separate papers:

Paper No. 1: Chemistry of Stored Swine Manure: A Geochemical Approach
Paper No. 2: Design of a Groundwater Monitoring System for Earthen Manure Storages
Paper No. 3: Long Term Monitoring Results from Three Earthen Manure Storages in Saskatchewan
Paper No. 4: Characterization and Propagation of a Hog Manure Seepage Plume in a Sandy Saskatchewan Soil

Paper No.1 discusses the chemistry of samples taken from seven hog manure storages. The samples were filtered to 0.45 μm and analyzed for major ions, dissolved organic carbon, dissolved inorganic carbon and metals. Filtering to 0.45 μm was assumed to separate out the portion of the solution that would be filtered by the soil below the EMS and the resulting solution would then represent the solution that could potentially transport through the underlying soils.

Paper No. 2 discusses the design process, design and installation of the monitoring system used for monitoring the three new EMS. The report also cover sampling and data collection protocols used at the sites.

Paper No. 3 discusses the results of sampling and data collection at the three EMS that have been monitored since their commissioning. Groundwater chemistry analysis results and water table changes with time are plotted over the site geographic cross sections.

Paper No. 4 discusses the characterization of the plume at the non-engineered EMS constructed in the sandy soils. This paper is the result of several projects including a portion of a Ph.D. thesis. The paper also outlines and discusses the propagation of the plume over the monitoring period.

SUMMARY

Background

The main objectives of this project were to set up a monitoring program to provide data regarding the long term performance and safety of earthen hog manure storages. In order to reach this objective it was necessary to monitor newly constructed storages, but also to complete detailed investigations of an existing older storage. The data collected from this project should increase public assurance and investor confidence in the hog industry. Results will also confirm the role of liners in new storages, the site characteristics required for establishment of new storages and possible requirements for decommissioning.

A detailed characterization of EMS effluent chemistry was not available in the literature. Therefore, it was deemed necessary to understand the source chemistry we were dealing with before being able to implement a monitoring program and obtain conclusive results.

Source chemistry

A detailed characterization of EMS effluent chemistry was conducted. In order to characterize the source chemistry of a typical EMS, a number of different EMS at hog production facilities were sampled. The samples were passed through a 45 μm filter prior to analysis because it was assumed fluid passing a 0.45 μm filter could potentially transport from an EMS to the surrounding groundwaters. The results showed that ammonium and bicarbonate are the most abundant species in EMS effluent at 36% each of the total molar concentration. Potassium and chloride follow at 8 and 6%, respectively. Sodium and sulphate make up the rest of the solution at 5 and 1%, respectively.

The species of most concern in EMS seepage is nitrogen. Ammonium is the most abundant form of nitrogen in the EMS effluents studied. Potassium and sodium may be cations of concern because they will likely compete with ammonium for soil exchange sites. This competition will influence the attenuation of ammonium. High concentrations of bicarbonate may affect the precipitation of carbonaceous minerals and may affect solution pH.

EMS monitoring

Groundwater chemistry at four EMS sites was studied for a period of seven years. Three of the sites (A, B, and C) had similar monitoring systems installed as the storage was being constructed. The fourth site (No. 1) was an existing EMS and unique monitoring equipment was installed as such. Sites A, B, and C have two earthen manure storages at each site, Cell 1 (solids) and Cell 2 (liquid).

All three, newly constructed EMS sites developed groundwater mounds after filling. The maximum mound elevation appears to reflect the high water level of the storage. The mounds did not appear to dissipate when the storage is emptied causing groundwater discharge heads in Cell 2 of the storage for several months of the year.

Site A

Site A is a 600 sow farrow-to-finish research and production unit that is serviced by an engineered two-cell EMS providing 400 days of effluent storage. A 600 mm thick recompacted clay liner was placed on the bottom of the storage with one metre thick liner built on the sides.

The land surface at this site is defined as moderately rolling to undulating with glacial lacustrine - alluvial plains. Examination of an aerial photograph of the area reveals a surface with many potholes, indicating poor surface drainage. The property is located in the Saskatchewan Rivers Plain physiographic region. Surficial soil is characterized as variable textured lacustrine and alluvial sands, silts and clays. The upper 30 to 40 m of this site consists of glacial till and stratified drift. This is underlain by 30 to 50 m of the Bearpaw formation (non-calcareous silty clay shale), followed by 20 to 30 m of the Judith River formation (non-calcareous sand, silt and clay) and 270 m of the Lea Park Formation - Upper Colorado Group (silty clay-shale).

Liner construction and monitoring system installation was completed during November of 1999. The automated reading systems for redox and temperature instruments, as well as the boards for pneumatic piezometres and water sample tubing were installed in Spring of 2000. Additional drilling was conducted by Prairie Farm Rehabilitation Administration (PFRA) and the University of Saskatchewan (U of S) in October of 2000. Standpipe piezometres and pneumatic piezometres were installed at several locations surrounding the EMS storages.

After installation, the groundwater samples were analyzed annually from 2000 to 2005.

Groundwater monitoring at this site indicates elevated ion concentrations (greater than 10 meq/L) immediately below the EMS to a depth of 1 m and below the inside slope of the storage to a depth of 3 m. These elevated concentrations appear to be the result of EMS seepage. Elevated ion concentrations at greater distances outside of this proximity to the EMS appear to be the result of mineral dissolution indicated by high levels of magnesium and sulphate.

Cell 2 at this site has experienced transport of ions to depths greater then three metres below the storage and distances up to 10 metres adjacent to the side of the storage. This is indicated by elevated concentrations of chloride, ammonium, potassium, sodium, magnesium, calcium and electrical conductivity readings in the same locations. This seepage is due to drying and cracking of the liner after it was installed as it remained empty for approximately one year before being used.

Site B

Site B is a 10,000 head hog finishing barn serviced by an engineering two-cell EMS facility with a capacity for 400 days of effluent storage. The storages were constructed during the summer of 1998.

This site is located on the northern fringe of the Quill Lake Plain. This physiographic region is characterized by the presence of glacial till and glaciofluvial plains. The topography is gently undulating to rolling. The top 60 m at this site consist of glacial till and stratified drift underlain by approximately 180 m of bedrock from the Riding Mountain Formation. This formation is non-calcareous silty clay, with fine sand interbedded within the top 60 m.

Liner construction and monitoring system installation was completed during June of 1998. Additional holes were drilled on July 5 to 7 and again on August 26 to 31 of 1999 by PFRA and University of Saskatchewan. Standpipe piezometres were installed in 17 of these, with pneumatic piezometres placed in two. These additional piezometres were placed around the primary cell to more closely monitor observed groundwater mounding.

The groundwater all locations at Site B were sampled annually from 2000 to 2005.

Groundwater monitoring at this site indicate seepage below and adjacent to Cell 1. Elevate ion concentrations (ion concentrations greater than 10 meq/L) occur to a depth of 0.5 m below the storage and extend approximately 3 to 6 m west of the side slope. This is indicated by chloride, alkalinity, ammonium, potassium, and sodium, as well as sulphate reduction in the same area. This seepage may be due to liner damage during agitation of the cell while being emptied.

Ion concentrations below Cell 2 indicate minimal seepage. Neither ammonium or potassium has transported more than 0.5 metres below the storage or 1.5 to 3 metres out from the side of the storage. Chloride and alkalinity concentrations appear to extend to depth of 1.5 to 3 m below the EMS and extend 6 to 8 m west of the inside toes of the slope. The area of elevated chloride concentrations appear to correlate with areas of elevated sodium concentrations and the area of elevated alkalinity appear to correlate with areas of high calcium concentrations. This may indicate that chloride and alkalinity are being affected by sodium chloride and calcite concentrations within the parent material or ammonium and potassium are significantly attenuated with respect to these anions. The liner in Cell 2 was not damaged due to agitation during emptying.

Site C

Site C is a 1200 sow nucleus unit serviced by an engineering two-cell EMS constructed to provide 400 days of effluent storage.

Topsoil was stripped from the surface before storage construction was begun. After digging out the storage depth, the clay till present at the site was compacted into a 600 mm thick liner in the storage. Liner construction was performed as per standards recommended by the consulting engineers.

The property is situated within the physiographic region Touchwood Hills Upland. This is characterized by rolling morainic plains and till plains with moderately undulating to strongly rolling topography. The upper 200 m consist of glacial till and stratified drift followed by approximately 150 m of silty clay-shale of the Lea Park Formation - Upper Colorado Group

Liner construction and installation of the monitoring system was completed in July 1999.

The groundwater all locations at Site C were sampled annually from 2000 to 2005.

Groundwater monitoring at Cell 1 indicate that elevated ion concentrations do not appear to extend more than 3 m adjacent to the mid point of the inside side slopes. This transport pattern is indicated by elevated concentrations of chloride, ammonium, potassium, reduced levels of sulphate and electrical conductivity readings.

Cell 2 has elevated ion concentrations to depth of 1 m below the cell and 3 to 8 m adjacent to the toe of the inside slope. This pattern is indicated by elevated concentrations of chloride, sodium, sulphate reduction and elevated electrical conductivity readings.

Site No. 1

Site No. 1 was constructed in 1984 to service a 250 sow farrow to finish operation which produces approximately 7300 m^3 of effluent per year. The site was constructed in a lacustrine deposit: soils consist of approximately 6 to 8 m of sands with lenses of silts and clays over lying at least four to six metres (maximum depth of investigation) of firm clay with lenses of sands and silts.

On February 15 to 19, 1999, PFRA and the U of S installed monitor wells and obtained soil samples adjacent to the EMS. Piezometre nests were installed in a line running south from the EMS, which was determined to be the general direction of groundwater flow by previous studies (Fonstad and Maule, 1995).

On March 22, 1999, drilling was completed through the ice in the EMS. Drilling was accomplished with a rotary drill rig using a hollow stem auger and Shelby tubes for sampling. The rig was parked on the ice surface of the EMS and the hollow stem auger drilled down to the soil surface.

In June 2005, the University of Waterloo, in conjunction with the University of Saskatchewan, installed multilevel piezometres in several locations at the site. An electromagnetic survey of the site was conducted to determine the need for more piezometres where the plume was not previously monitored.

The groundwater at all locations at Site No. 1 were sampled annually from 2000 to 2005.

The results of the groundwater sampling show that multispecies transport through the sandy material at this site has resulted in a plume consisting of a hardness halo at the edge of the plume and attenuation of ammonium and potassium with respect to chloride. The entire plume extends approximately 70 metres out from the EMS. Ammonium and potassium transport are retarded by factors of approximately 2 and 4, respectively. This relatively low retardation factor of ammonium should be of concern when EMS sites.

CONCLUSIONS

Ammonium nitrogen and bicarbonate were determined to be the major species in EMS effluent. Since nitrogen is an ion of concern, the seepage of EMS effluent is important to monitor.

The groundwater samples indicate that seepage has resulted in elevated ion concentrations (greater than 10 meq/L) to depths of up to 1.5 m below some of the newly constructed storage cells and to distances of up to 10 m directly from the toe of the inside slope of the EMS since their commissioning between 1998 and 1999. These elevated ion concentrations are found in storages that were not operated properly (allowed to dry and crack) or that were damaged during emptying. Groundwater mounds have developed in the vicinity of all three EMS constructed in clay and/or clay till material.

The plume that has formed at the non-engineered EMS at Site No. 1 has been valuable to study multispecies transport through a sandy material. Ion exchange mechanisms are visible within the plume and ammonium is attenuated at relatively low retardation factors. This site shows the importance of site characteristics when constructing an EMS.

Publications and Presentations as a Result of this Project

Publications:

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Swine Manure Chemistry: A Geochemical Perspective

Paper No. 1

ADF Project # 20000265

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Prepared by:

T. A. Fonstad, Ph.D., P.Eng. and Crystal Rinas, B.E.
Department of Agricultural and Bioresource Engineering
University of Saskatchewan

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INTRODUCTION

Saskatchewan Agriculture, Food and Rural Revitalization (SAFRR, 1997), MidWest Plan Service (MWPS, 2000) and other organizations, give values for major nutrient concentrations of manure. These values are averages and are useful as general guidelines since actual nutrient values may vary widely, depending on many factors such as animal age, animal diet, type of storage, and manure handling system (Reick-Hinz et al., 1996; Bayne 1997; Campbell et. al., 1997). The literature generally contains information regarding macronutrient concentrations (N, P, K, and S), and micronutrient concentrations (Cu, Mn, and Z). The values cited are generally for the total effluent mix of solids and liquids or as mass excreted per kilogram of animal weight.

Detailed characterization of EMS effluent chemistry was identified as one of the deficiencies in the literature. Hog production facilities are of four general types: farrowing units, where mainly sows are housed; nursery units, where piglets from 10 to 60 days of age are housed; finishing units, where pigs from 60 to 180 days are housed; and farrow to finish units where all three are housed together. As a result, at least two manure storages of each type of facility were sampled. Samples were filtered through a 0.45 μm filter and analyzed for major and minor ions.

BACKGROUND

A study in Canada to characterize hog manure storages was conducted by Campbell et.al. (1997) in Prince Edward Island. This involved determination of the variation of solids content and chemistry with depth. The results of this study may not completely reflect solids content as a function of depth as the sampler used was fitted with a 7-mm screen. Concentrations of various ions were reported to be in line with earlier studies in Canada, the United States and Europe. No carbonate chemistry was reported and only ammonium was analyzed for the liquid fraction alone. For comparison, Iowa State University conducted a study of 183 swine manure pits that entailed retrieving samples using a 12-foot long plastic tube or as grab samples during agitation while emptying the storage (Lorimor et al., 1997). Both studies reported quite variable results. Campbell et.al. (1997) reported dry matter contents ranging from 1.8% to 5.4% while Lorimor et al. (1997) reported dry matter contents ranging from 1.2% to 18.1%. Campbell et al. (1997) reported ammonium and potassium concentrations ranging from 1450 mg/L to 5670 mg/L and 690 mg/L to 2970 mg/L respectively, while Lorimor et al. (1997) reported concentrations ranging from 2300 mg/L to 16,000 mg/L and 370 mg/L to 3100 mg/L respectively. This large variation in ammonium concentration may be a result of variations in solids content or animal diet. No studies were found that reported filtering of samples prior to the analysis and/or analysis of both major cations and anions

The literature highlights the difficulty of obtaining a representative sample from an EMS pond. In order to obtain accurate field information regarding the characteristics of the manure and how those characteristics change with depth, it is necessary to utilize a sampler that would retrieve distinct samples at any depth. Samplers used by researchers for this purpose vary widely in configuration and operation. Lorimor et al. (1997) used a PVC tube with a manually operated ball valve on the bottom. Booram et al. (1975) used a Plexiglass tube pushed through

to the bottom of the lagoon. These samplers do not retrieve samples at specified depths but rather an integrated sample of the vertical profile. Campbell et al. (1997) used a peristaltic pump attached to a sampling line that contained a 175-mm long strainer with 7-mm inlets. It was felt that this sampler would not retrieve representative samples in dense manure with high solids content, and difficulty was reported in obtaining a representative sample at various depths in the storage. The Kroes-Barth-Dodd sampler (Kroes et al., 1987) sampler takes distinct samples at any lagoon depth and is reported to have worked well at solids concentrations of up to 21% (Barth et al., 1985).

METHODOLOGY

In order to characterize the source chemistry of a typical EMS, a number of different EMS ponds at hog production facilities in Saskatchewan were sampled. These included two EMS servicing farrow to finish operations, two servicing farrow to wean operations and three servicing finishing operations. Each EMS was sampled at depths of 0.1, 1.0, and each subsequent meter to depth. Samples were sent to the Saskatchewan Research Council Analytical Laboratory in Saskatoon, Saskatchewan for filtering and analysis.

Instrument design

The sampler was constructed of a 0.3m length of ABS pipe connected to two ABS gate valves (Figure 1). Lengths of stainless steel pipe acted as the handle of the sampler and more lengths were connected to reach the various sampling depths as required. A stainless steel rod connected to both valves and passing through the handle was used to actuate the valves.

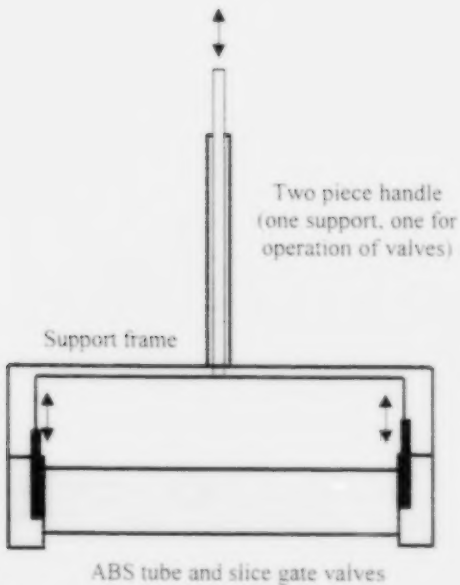

Figure 1. EMS sampling apparatus.

Sampling procedure

Sampling was conducted from a boat on the EMS pond. The sampler was lowered to the desired depth with the gate valves closed. The valves were then opened by pulling the inner handle rod and the sampler pulled sideways to get a representative sample at that depth. The gate valves were then closed and the sampler was brought to the surface to be emptied into a one-liter container.

Sample handling and analysis

Samples were placed in sealed plastic containers and transported to Saskatchewan Research Council Analytical Laboratory in Saskatoon, Saskatchewan where EC, pH, and Total Solids analysis on the mixed sample were measured. A portion of the sample was then filtered through a 0.45 µm filter. The filtered sample was split for analysis of alkalinity, major ions, metals, total ammonium, nitrate, nitrite and sulphide.

Major ions (Ca, Mg, Na, K and SO_4^{2-}) where analyzed by ICP-IRS, carbonates (HCO3-, CO3 and alkalinity) by acid titration, nitrogen and chloride by colorimetric method, sulphide and pH by electrode, organic carbon by Dohrman Pheonix carbon analyzer and metals were analyzed by ICP-AES.

Filtered sample analysis

Tables 1 and 2 provide the results of analyses by the Saskatchewan Research Council Laboratory in units of mg/L and meq/L respectively. All samples were filtered to 0.45µm prior to analysis.

Speciation of the samples was determined using PHREEQC (Parkhurst and Appelo, 1999). Figure 2 and 3 provides a bar graph of the concentration in mg/L and meq/L, respectively, for the nine most abundant ions and organic carbon. The results have been corrected for speciation using PHREEQC. Figure 4 provides a bar graph of the same data converted to molality. Figure 5 provides a bar graph of the activity of the most abundant ions as determined by using PHREEQC.

The data shows that bicarbonate (HCO_3^-)is the major anion and ammonium-nitrogen [NH_4^+ or N(-3)] is the major cation for all samples. Potassium (K^+) and chloride (Cl-) are also significant with some sodium (Na^+) and sulfate [SO_4^{-2} or S(6)]. Although there is some variance between the six sites, all the results indicate that the major cation is ammonium and the major anion is bicarbonate. These ions are rarely used in tracer studies or studied in transport modeling. The lesser ion of chloride is the most commonly used tracer ion in investigations of EMS while potassium (K), an ion of similar activity, is rarely considered.

Variances in the data could be the result of differences in water source, feed mixes and age of the animals.

Calculated Eh values using the S(-2)/S(-6) redox couple ranged between –197mV and –270mV (Table 1).

The prediction of speciation for all samples produced similar orders of abundance. This is expected, since all these samples have high bicarbonate and ammonium levels, low Eh and neutral pH conditions. Any variation in species abundance was mainly the result of variation in sulphate concentrations. Although calcium and magnesium are important in terms of molar concentrations, their relatively low activity concentrations at the ionic strengths indicated produce relatively low activities for these ions as compared with the major ions, sulphate and bicarbonate. As a result, the ions with the highest activities in the seven manure samples were ammonium, bicarbonate, potassium, chloride, sodium, carbon dioxide gas, sulphate and ammonia (Figure 5).

The individual ion concentrations from the speciation of each solution were divided by the total molality or activity to attempt to normalize the data for all sites. Results of this exercise are given in Figures 6 and 7 and are summarized in Table 3:

Table 3. Concentration of the most abundant ions in EMS effluent from seven sites in Saskatchewan. Values average percent of total and (average standard deviation).

Ion	Molality	Activity
Ammonium ($NH4^+$)	36% (2%)	34% (1%)
Bicarbonate ($HCO3^-$)	36% (3%)	38% (3%)
Potassium (K^+)	8% (2%)	8% (1%)
Chloride (Cl^-)	6% (1%)	6% (1%)
Sodium (Na^+)	5% (2%)	5% (2%)
Suphate ($SO4^{-2}$)	1% (1%)	< 1%
Carbon Dioxide ($CO2$)	3% (3%)	4% (4%)

As indicated in Table 3, the relative concentration of the four most abundant ions in all seven samples was similar. This information suggests that an approximation of the concentration of these should be attainable knowing the total concentration of ions in solution. Differences between samples could be the result of animal age and feed and water chemistry.

CONCLUSION

The species of most concern in EMS leachate is nitrogen. This study indicates that ammonium nitrogen is the most abundant form of nitrogen and one of the most abundant ions in EMS effluent. Other cations of concern may be potassium and sodium, as they will likely compete with ammonium for soil exchange sites affecting the attenuation of the ammonium. Bicarbonate and chloride are by far the most abundant anions with bicarbonate being significantly more abundant than chloride. These relatively high concentrations of bicarbonate will likely affect precipitation of carbonaceous minerals and may have an affect on solution pH.

Table 1. Results of analysis of filtered swine manure samples (mg/L)

Source		ADF Research Site 1	ADF Research Site 9	Big Sky 1 Farrowing Unit	Clearfield Feeder Unit	PSC Elstow Research Farm	Peterson	MacKay (Aerated)				
	units	F to F	F to W	F to W	Feeder	F to F	Feeder		Ave.	St.Dev.	Min.	Max.
pH		8.27	6.94	7.33	7.66	8.26	7.68	7.1	7.61	0.52	6.94	8.27
Ammonium N	mg/L	3716	2957	1903	3729	4147	3941	6763	3879	1483	1903	6763
Potassium	mg/L	2400	1230	740	1840	1720	2060	4170	2023	1092	740	4170
Sodium	mg/L	529	330	490	1260	394		1400	734	469	330	1400
Calcium	mg/L	90	210	75	502	72		191	190	164	72	502
Magnesium	mg/L	2.7	13	250	301	0.8		9.4	96.2	139.9	0.8	301
Alkalinity	mg/L $CaCO_3$	12200	7400	5810	12800	12700	11000	20000	11701	4565	5810	20000
Chloride	mg/L	1590	1030	575	1180	1300	1160	2620	1351	638	575	2620
Sulfate	mg/L	357	1300	1150	933	316	78	761	699	461	78	1300
Sulfide	mg/L	0.02	27			0.04	36.7		15.9	18.8	0.02	36.7
Nitrate as N	mg/L	2.3		1	1.5	12	0.32	4.7	3.6	4.4	0.32	12
Nitrite as N	mg/L	2.2	0.03	0.05	0.17	5.9	0.02		1.40	2.37	0.02	5.9
Phosphorus	mg/L	350	110	4.8	8.1	120		93	114	126	4.8	350
Silicon	mg/L	81	64	47	86	30			62	23	30	86
Iron	mg/L	0.79	4.5	4.3	6.7	0.11			3.28	2.76	0.11	6.7
Boron	mg/L	0.71	1.1	0.51	1.2	2.1			1.12	0.61	0.51	2.1
Strontium	mg/L	0.34	0.43	0.5	3.5	0.46			1.05	1.37	0.34	3.5
Zinc	mg/L	0.042	5.1	0.01	0.019	0.002			1.03	2.27	0.002	5.1
Manganese	mg/L	0.054	0.38	0.04	3.5	0.096			0.81	1.51	0.04	3.5
Barium	mg/L	0.087	0.064	0.028	0.54	0.02			0.15	0.22	0.02	0.54
Copper	mg/L	0.016	0.41	0.015	0.004	0.006			0.09	0.18	0.004	0.41
Lead	mg/L	0.2	0.007		0.002	0.002			0.05	0.10	0.002	0.2
Inorg. Carb.	mg/L	9230	1780	1390	2580	2500						
Org. Carb.	mg/L	6300	3900	550	9300	5500						

Table 2. Results of analysis of filtered swine manure samples (meq/L)

Source		ADF Research Site 1	ADF Research Site 9	Big Sky 1 Farrowing Unit	Clearfield Feeder Unit	PSC Elstow Research Farm	Peterson	MacKay (Aerated)				
Sample No.		F to F	F to W	F to W	Feeder	F to F	Feeder	Feeder				
	units								Average	Standard Deviation	Min	Max
pH		8.27	6.94	7.33	7.66	8.26	7.68	7.1	7.61	0.52	6.94	8.27
Ammonium N	meq/L	206	164	105	207	230	218	375	215	82	105	375
Potassium	meq/L	61	31	19	47	44	53	107	52	28	19	107
Sodium	meq/L	23	14	21	55	17		61	32	20	14	61
Calcium	meq/L	4	10	4	25	4		10	9	8	4	25
Magnesium	meq/L	0.2	1.1	20.6	24.8	0.1		0.8	7.9	11.5	0.1	24.8
Alkalinity	meq/L	244	148	116	256	254	220	400	234	91	116	400
Chloride	meq/L	45	29	16	33	37	33	74	38	18	16	74
Sulfate	meq/L	7	27	24	19	7	2	16	15	10	2	27
Sulfide	meq/L	0.001	0.8			0.001	1.1		0.5	0.6	0.001	1.11
Nitrate as N	meq/L	0.037		0.016	0.024	0.194	0.005	0.076	0.1	0.1	0.005	0.194
Nitrite as N	meq/L	0.0478	0.0007	0.0011	0.0037	0.1283	0.0004		0.03	0.05	0.0004	0.128
Phosphorus	meq/L	11.3	3.6	0.2	0.3	3.9		3.0	4	4	0.2	11.3
Silicon	meq/L	2.9	2.3	1.7	3.1	1.1			2	1	1	3
Iron	meq/L	0.014	0.081	0.077	0.120	0.002			0.06	0.05	0.002	0.120
Boron	meq/L	0.07	0.10	0.05	0.11	0.19			0.10	0.06	0.05	0.19
Strontium	meq/L	0.004	0.005	0.006	0.040	0.005			0.01	0.02	0.004	0.040
Zinc	meq/L	0.00064	0.07802	0.00015	0.00029	0.00003			0.02	0.03	0.00003	0.078
Manganese	meq/L	0.00098	0.00692	0.00073	0.06371	0.00175			0.01	0.03	0.0007	0.064
Barium	meq/L	0.00063	0.00047	0.00020	0.00393	0.00015			0.001	0.002	0.0001	0.004
Copper	meq/L	0.00025	0.00645	0.00024	0.00006	0.00009			0.001	0.003	0.00006	0.006
Lead	meq/L	0.00097	0.00003		0.00001	0.00001			0.0003	0.0005	0.00001	0.001

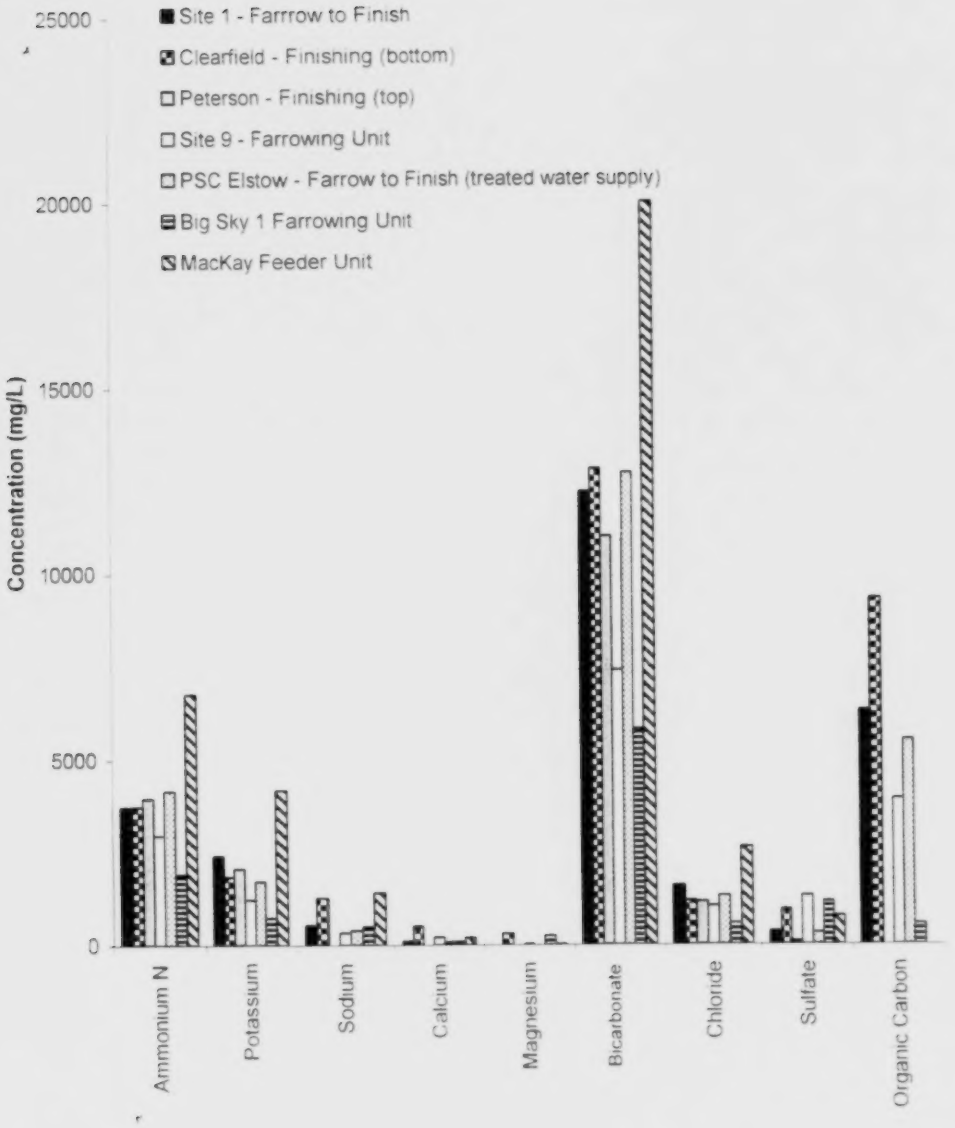

Figure 2. Eight most abundant ions and organic carbon concentrations in filtered swine manure samples (mg/L)

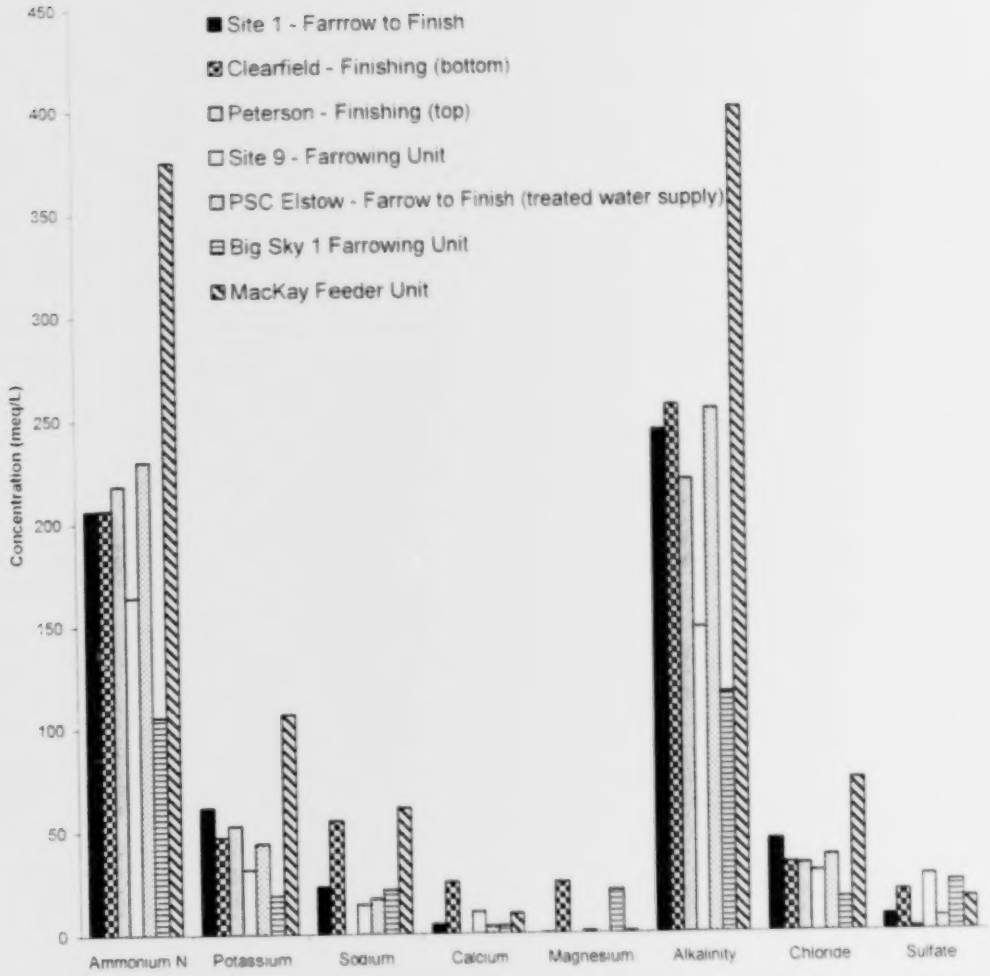

Figure 3. Concentration of the eight most abundant ions in filtered swine manure samples (meq/L)

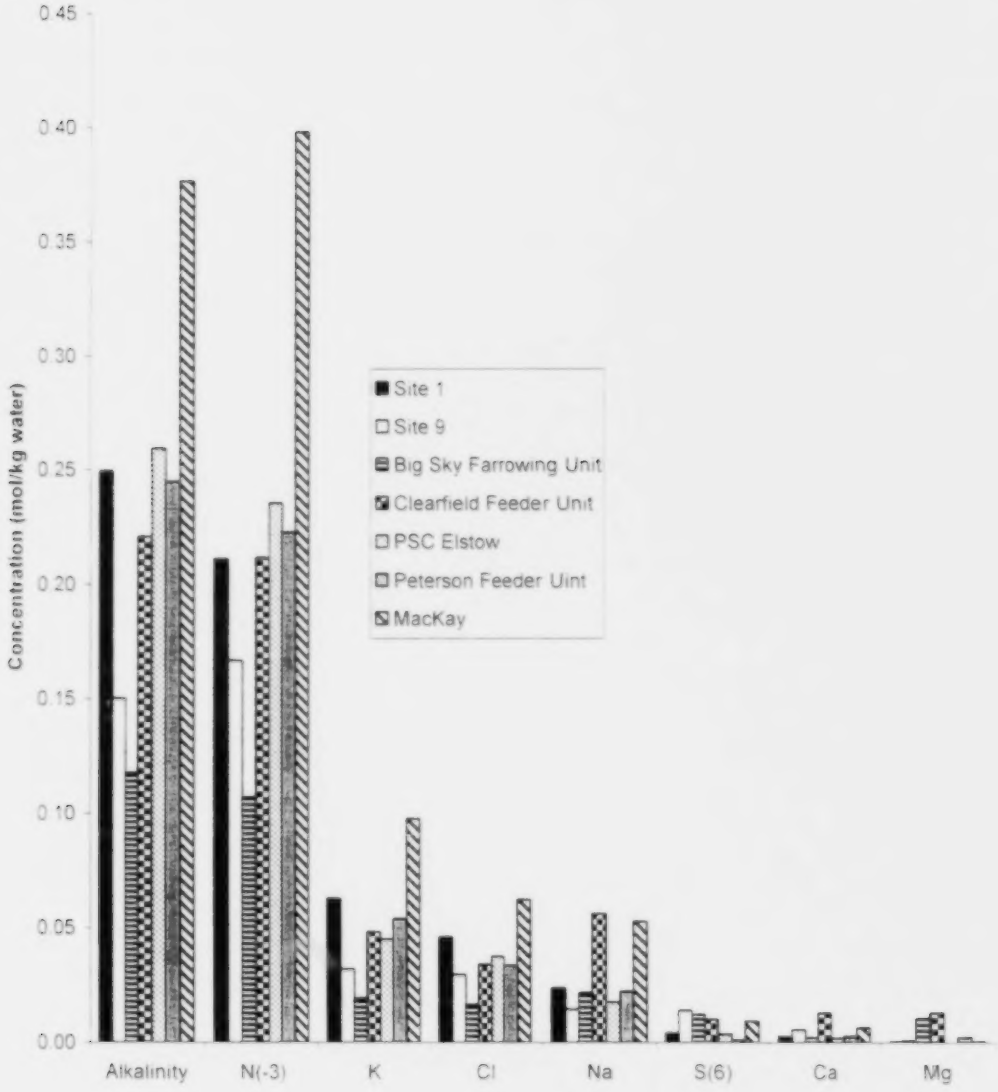

Figure 4. Concentration (molality) of the eight most abundant ions in filtered swine manure samples (mol/kg water)

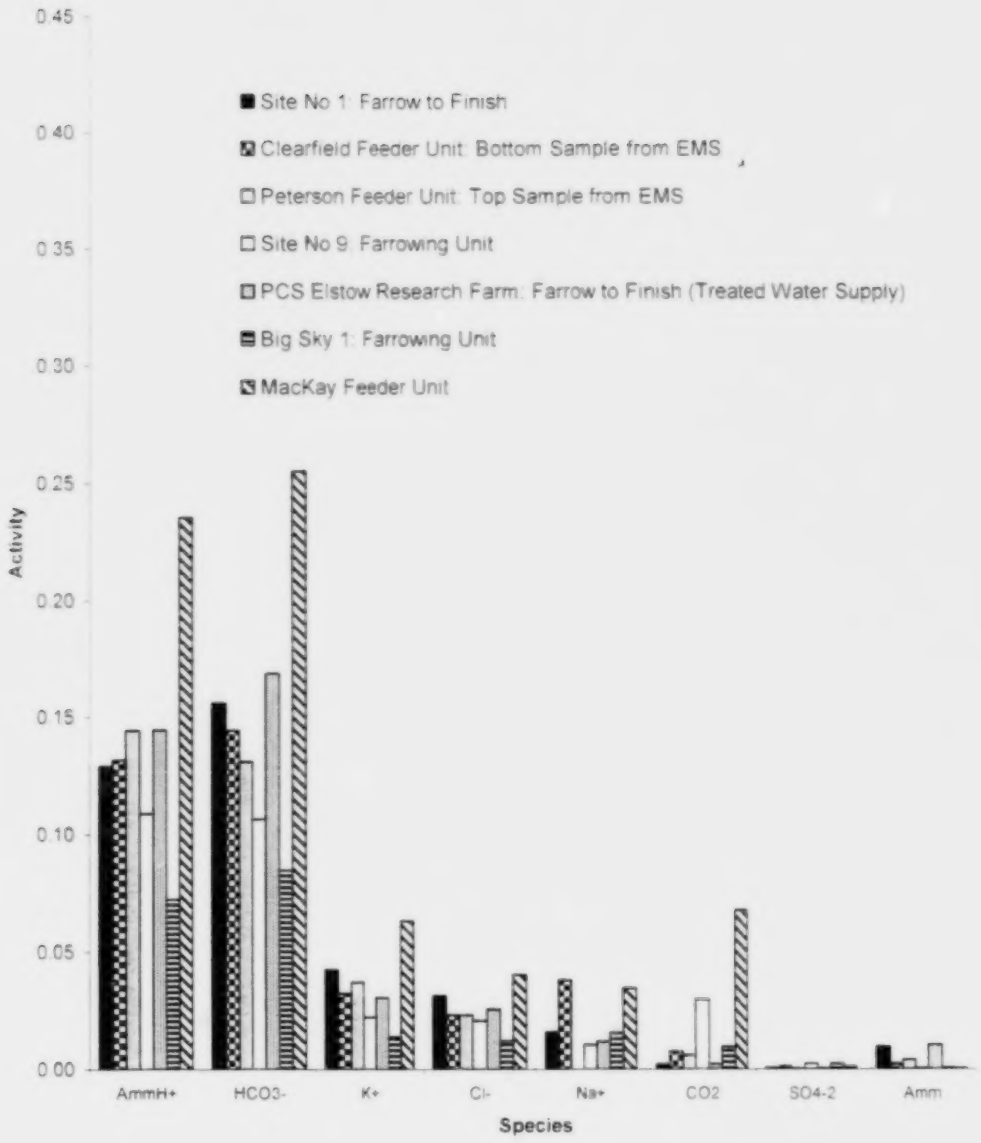

Figure 5. Activity of the eight most abundant ions in filtered swine manure samples

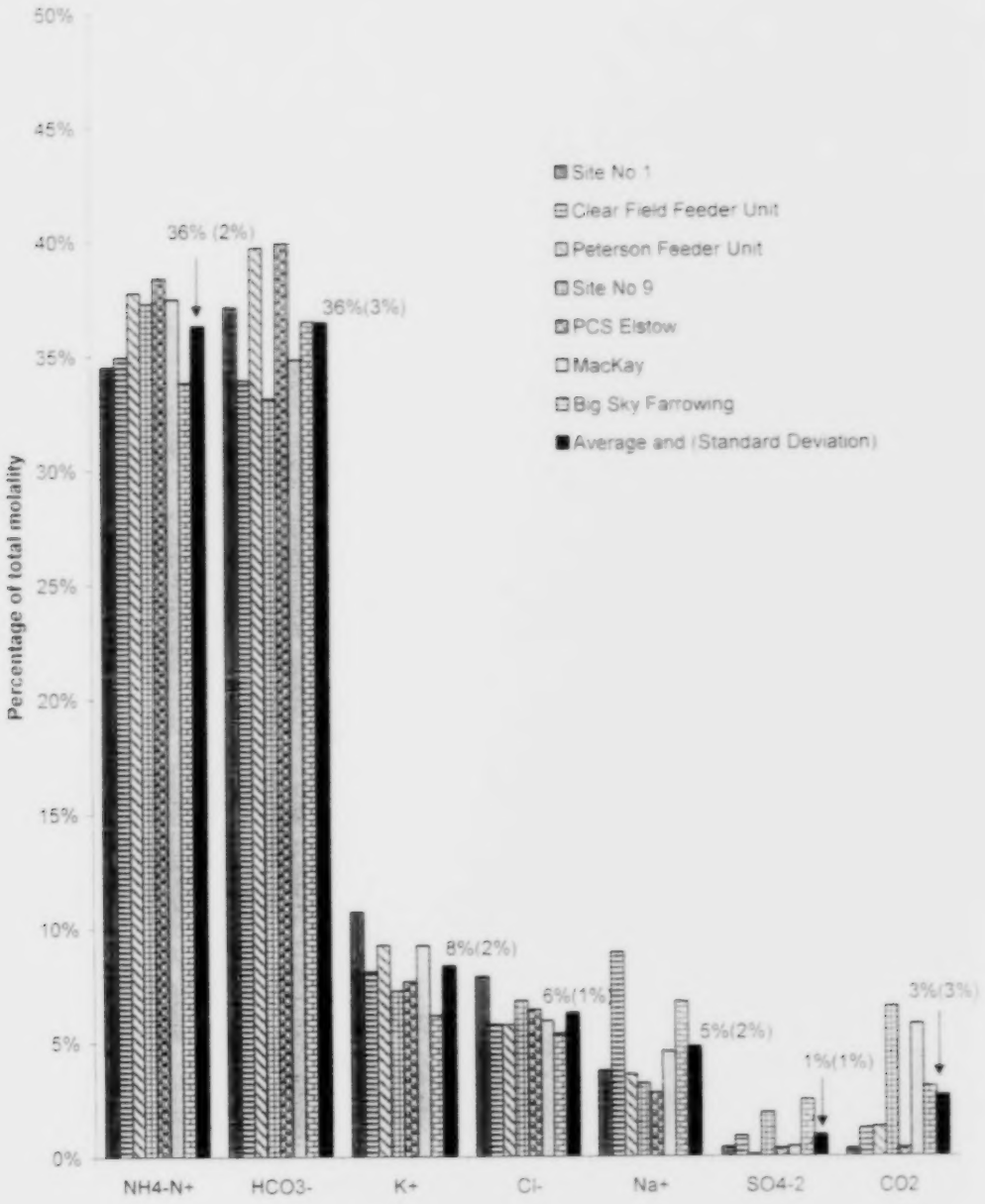

Figure 6. Percentage of total molality of the six most abundant ions and carbon dioxide in filtered swine manure samples

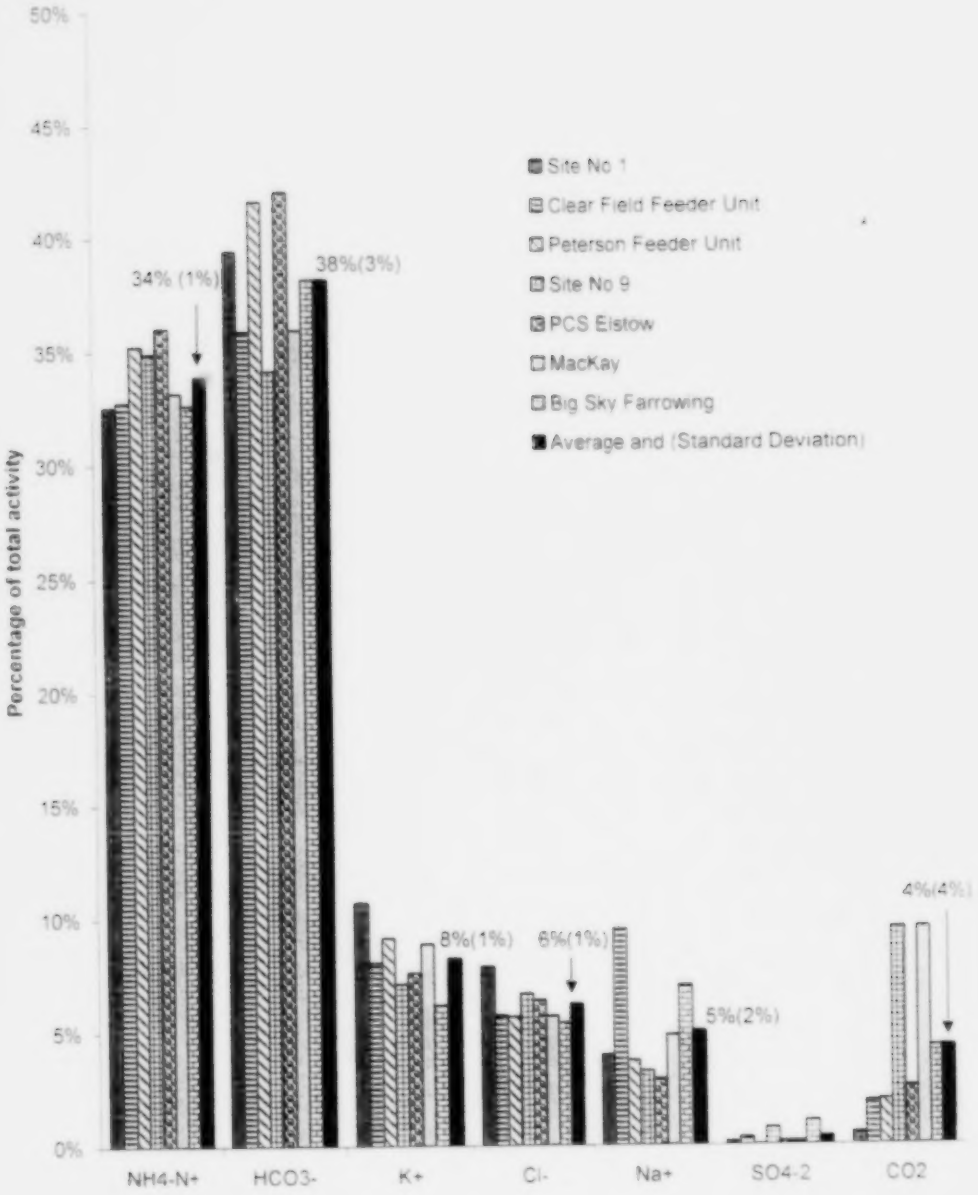

Figure 7. Percentage of total molality of the six most abundant ions and carbon dioxide in filtered swine manure samples

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Design of a Groundwater Monitoring System for Earthen Manure Storages

Paper No. 2

ADF Project # 20000265

Report Submitted to:
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Prepared by:

T. A. Fonstad, Ph.D., P.Eng. and Crystal Rinas, B.E.
Department of Agricultural and Bioresource Engineering
University of Saskatchewan

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ABSTRACT

In 1997, the University of Saskatchewan and the Prairie Farm Rehabilitation Administration were asked to design a monitoring system to test the long-term performance of earthen manure storages (EMS). The minimum design needed to measure hydraulic head, temperature, oxidation-reduction potential, and allow for extraction of water samples. Additionally, the system materials cost was to be kept below $ 15,000. The system designed consisted of 24 piezometeric tips at 4 locations and various depths within each cell of an EMS. Tips have a pneumatic piezometer (or are standpipes), a thermocouple, a platinum redox probe, and two 3.2 mm diameter tubes. To date this system has been installed in the EMS at a 10,000 hog finishing facility, a 1200 sow farrow to finish facility and a 600 sow farrow to finish research facility. Systems have been sampled annually for five years as part of the project and will continue to be sampled biannually until at least 2009. Data from the sites will be used to determine seepage potential and develop models to predict EMS seepage transport. This paper outlines the design of the monitoring system, installation procedures, sampling procedures, example sampling results and considerations for improvement.

INTRODUCTION

Earthen manure storage leachate contains high levels of ammonium, potassium, sodium, bicarbonate, chloride and sulphate (Fonstad 2004). Seepage of this solution into soils surrounding an EMS can constitute a potential groundwater contamination concern. The fate of ammonium in the groundwater has been a primary motivation for monitoring of earthen manure storages because the presence of elevated levels of nitrate in the groundwater can be an environmental health concern. Therefore, it is necessary to determine the extent of seepage from established operations and to prevent seepage from new operations. The objective of this paper was to document the design of a monitoring system for newly constructed earthen manure storages.

Literature review

Accurate measurement of emerging seepage and delineation of existing seepage plumes have been attempted using a variety of methods including analysis of soil samples, water sampling from shallow wells, remote sensing, redox zoning, and other more site specific and complex systems. Each of these methods has been applied to different conditions with various results.

Soil samples from the bottom of EMS have been studied to determine the extent of contaminant migration by Miller et al. (1976), Filson (1994), and Fonstad and Maule (1996). Both Miller et al. (1976) and Fonstad and Maule (1996) found significant movement of chloride, ammonium, and potassium below EMS constructed in coarse textured soils and layered alluvial deposits. Coring of soils beneath EMS have all indicated some seepage. Ten to twenty year old storages have demonstrated seepage to depths of at least 2 to 4 m in clayey soils and 5 to 10 m in layered sandy soils. This would appear to indicate that investigations for new storages constructed in clayey soils should be conducted to depths of at least three metres below the EMS floor.

Plume determination through the installation of shallow monitoring wells has been completed in Virginia (Ciravolo et al. 1979), Deleware (Ritter et al. 1980), North Carolina (Huffman and Westerman 1995; Westerman et al. 1993), and Ontario (Miller 1985). Monitoring well installations near EMS have found horizontal seepage in sandy deposits and granular lens in clays soils of a least 60 m in 15 years or less. Nitrogen transport was found to be the result of ammonium in the EMS in all cases reviewed.

The most difficult task when using groundwater as an indicator of contaminant migraton is obtaining a representative sample (U.S. EPA 1995; Gosselin et al. 1994; Boulding 1993; Robbins and Martin-Hayden 1991; Hartz 1991). First, hydrogeological variations in the aquifer may complicate well design and placement decisions (Gosselin et al. 1994; Robbins and Martin-Hayden 1991). Second, installation of the well may introduce new colloidal matter, the material may cause reactions with the contaminant, or the filter may remove naturally mobile colloids (U.S. EPA 1991; Puls and Barcelona 1989; Driscoll 1986). Third, purging methods for sample acquisition may introduce colloidal matter, cause degassing, or precipitation of dissolved contaminants (Boulding 1993; U.S. EPA 1991, Puls and Barcelona 1989; Driscoll 1986). Finally, sample transportation, storage, and analysis may cause degassing, precipitation, pH changes, temperature changes, and/or species alterations (U.S. EPA 1991; Pohlmann et al. 1994).

To overcome these problems parameters such as pH, gases and alkalinity should be determined in the field (Boulding 1993). When purging a well, it is recommended to pump the well at low flow rates (0.1 L/min to 1 L/min) until water indicators (pH, EC, Eh, temperature, and dissolved oxygen) stabilize (Boulding 1993, Puls and Barcelona 1989; Shanklin et al. 1995; Bone 1986).

Several researchers have attempted to determine the extent of solute migration from EMS through remote sensing, primarily electromagnetic (EM) surveys. An EM survey can provide insight to aid in the delineation of shallow groundwater plumes. The EM instruments send out an electrical signal that causes the generation of a secondary magnetic field. The amplitude of this field can then be related to the bulk electric conductivity of the soil, which can be related to in situ soil conditions and used to determine contamination.

Moffin et al. (1993) first evaluated soil properties vs. hydraulic conductivity followed by EM surveys on several sites in Texas and North Carolina. EM surveys were found to be inconclusive in determining seepage from EMS at these sites. Huffman and Westerman (1995) estimated nitrogen export from EMS using groundwater quality with plume tracing using EM surveys. The results of this work showed promise as the EM surveys appeared to correlate with the groundwater results. Drommerhausen et al. (1995) also found good results using EM survey near EMS and loafing areas for dairies. The best EM survey results appear to be in areas of deeper sand deposits with plumes that extend several tens to hundreds of metres from the source. EM was reported to be troublesome unless done in conjunction with soil drilling and sampling to determine site geology and stratigraphy. EM surveys can be very hard to interpret in soils with normally high electrical conductivity.

In Saskatchewan, earthen manure storages are typically located in clay or clay till materials. Installation of monitoring equipment in these materials is often difficult due to slow groundwater velocities. Groundwater mounds can be relatively extensive, as vertical velocities are generally less than horizontal velocities causing spreading of the mound.

DESIGN

Constraints and Criteria

The research group set out the following data requirements for a monitoring system:

Minimum:

- Hydrostatic pressure at relatively discreet points.
- Ability to obtain a water sample for chemical analysis.
- Temperature at the sampling point.

Optional:

- Soil suction profile at one location.
- Oxidation/Reduction (ORP, Eh, pE) potential at the sampling points.
- Dissolved gas-sampling ability.
- Hydraulic conductivity of the liner with time.

Other restrictions of the proposed system were that it had to be relatively easy to install, materials could not be more than $15,000 (CAN), and sampling and analysis should be relatively simple.

Two hypothesis were put forward as to what conditions would exist within the first several years after decommissioning. The first was that if the site water table were initially lower than the base of the EMS, a bulb of saturated soil would emanate from the EMS out until it encountered the water table and would then start to form a groundwater mound. The second was that if the site water table were initially above the base of the EMS, a groundwater mound would form over time. This left the research team with three options for a system that would give the best chance for quality samples over a long period of time (15 to 25 years). The first was the common gravel drain beds or lysimeters (Swanberg 1997; Ruhl 1999) used by other researchers, the second, a system to detect water movement and chemistry under unsaturated conditions and the third, a system to detect water movement and chemistry under saturated conditions.

Design Options

Option No. 1- Gravel collector beds The initial proposed system consisted of installing horizontal well screens in three-meter square gravel beds at various depths below the EMS. These horizontal wells would be graded to a sump where a sample could be retrieved for analysis.

Pros:

- Inexpensive and easy to install (low tech).
- Simple to sample.

Cons:

- Gravel collections beds could form a capillary break if they were kept drained and could then have bypass flow.
- Would need several beds at several depths to estimate flow velocities.
- Installation is intrusive to the liner and the material over the gravel bed may not be indicative of the rest of the liner. Additionally, inadequate compaction of the trench material could induce seepage to the sample point.
- Water volumes in the beds requiring purging would be significant.
- Water in the standpipe is able to react with the atmosphere that could change the chemistry, pH, etc.

Option No. 2 – Unsaturated Soil Monitoring Equipment This option was based on the hypothesis that a bulb of saturated soils would emanate from the EMS after commissioning. The option proposed installation of mini-piezometers for pressure head with suction tubes for sampling, TDR probes for moisture front tracing, suction lysimeters as backup for water samples, oxidation/reduction potential (ORP) probes, thermal conductivity sensors for soil suction, thermocouples and gas samplers.

Pros:

- Relatively accurate measurement of parameters and representative water samples.

Cons:

- Cost of materials is higher than our research group thought should be targeted.
- Installation required highly qualified technical staff.
- Measurement of the numerous instruments would be time consuming.
- Many of the instruments would be ineffective at moisture contents at or near saturation.
- Frost would could destroy many of the instruments.

Option No. 3 – Saturated Soil Monitoring System This option was based on the assumption that soils beneath the storage would reach full saturation soon after filling of the storage (i.e. they were already near saturation). The system proposed to bundle a short (0.45 m x 50 mm dia.) well screen with a pneumatic piezometer for pressure measurement, two-3.2 mm diameter plastic tubes for suction extraction of water samples, a thermocouple and a platinum ORP probe. In installations where there was no fluid ponding, the pneumatic piezometer would not be required and be replaced by a standpipe piezometer.

Pros:

- Relatively precise measurement of parameters and a good quality water sample
- Simple to install and could be installed after construction of the storage was complete.
- Measurement and sampling would be simple and temperature and ORP could be automated.
- System materials cost would allow installation of up to 24 sample bundles in each cell of a two-cell storage.

Cons:

- Some concern with sample degassing from suction sampling.
- Concern with the accuracy and interpretation of the ORP measurement.
- Sealing of installation boreholes and sampling line trenches.

Selection of an Optimum Design

The team reviewed approximately 25 site investigation reports from various EMS sites throughout the province. These reports revealed that the soils at the majority of the sites were at 90% to 100% saturated from one meter below grade to the water table. This indicated that it was likely that a groundwater mound would form relatively quickly in the clay till soils at the proposed research sites. After review of this information and the options presented, the research group decided to use Option No. 3 as it offered the best chance for a successful installation, should be durable and offered relatively high quality sampling.

INSTRUMENTATION CONSTRUCTION

Piezometers Piezometers were constructed using SCHD 40 PVC slotted and solid pipe. 50 mm diameter screened pipe was purchased with precut 0.1-inch slots. This screen pipe was cut into lengths, capped and fitted with a coupler to form a 500 mm long section with approximately 450 mm of exposed screened. Screens installed in wet conditions or silty soils were covered with a filter sock to reduce fines entering the screen. Piezometers to be installed in locations L1 to L4 (Figure 1) were fitted with 19 mm ID PVC SCHD 40 risers. Piezometers to be installed outside the berm of the EMS (nested piezometer locations) were fitter with 50 mm diameter PVC SCHD 40 risers. 19 mm piezometers were cased with 50 mm diameter PVC SCHD 40 from 150 below the ground surface to approximately 50 mm above the riser height. All risers were capped with SCHD 40 caps and threaded plugs.

Pneumatic Piezometers Pneumatic piezometers were purchased from RST Instruments Ltd., Coquitlam, British Columbia. Pneumatic piezometers are Model P-100 Minerature pneumatic piezometers. The model P-100 incorporates a 50 micron stainless steel screen, is capable of monitoring pore pressures from 0 to 13,000 kPa, and requires only 0.002 ml displacement allowing measurements to be made under low volume change conditions. Piezometers were ordered with the appropriate length of access tubing, fittings and calibrated from 0 kPa to 100 kPa. Each cell was equipped with a panel board that allows all piezometer tips to be plumbed

in and covered by a weatherproof access door. Reading is accomplished using a RST Instruments Ltd. Model C-106 Digital Pneumatic Readout instrument.

Thermocouples Thermocouples were constructed to measure insitu temperatures of the groundwater system. The thermocouples were constructed of 20-gauge Type T thermocouple wire and made in the manner suggested by Culik et al. (1982). The wire was cut to the desired length and approximately 25 mm of one end was stripped. The stripped wires were twisted together by clamping the end with pliers and turning the pliers until the wires had been evenly twisted 3 times. The twisted wires were then fluxed and soldered liberally with 40% lead, 60% tin solder. The soldered portion was cleaned thoroughly and clipped off to a length of approximately 10 mm. A 25 mm length of heat-shrink tubing with an adhesive inner wall was cut and placed so that it stuck over the soldered tip by about 5 mm. The tubing was heated using a heat gun until the adhesive appeared. The end of the tubing was then clamped using pliers. After cooling, the thermocouples were tested by measuring them at a known temperature.

ORP electrodes Oxidation-reduction potential (ORP) electrodes were constructed using a method similar to the method used by Farrell et al. (1991) to construct platinum electrodes suitable for long-term field measurements. A 12.5 mm (Farrell et.al., 1991) length of 20-gauge 99.99% pure platinum wire was cut and silver soldered (Simpson and Berberian 1976) to a length of 18-gauge copper cable with PVC casing. A hole just large enough for the platinum wire was punched through the bottom of a plastic syringe tip using a dental pick. Epoxy was mixed using 80 parts Glenmark GMI#80 hardener to 100 parts Glenmark GMI#1630 resin. The syringe tip was filled with the epoxy using a 20cc syringe with a 14-gauge needle. After filling the plastic tip with the epoxy, the platinum tip was threaded through the hole on the bottom of the syringe tip until approximately 10mm (Farrell et.al., 1991) of the platinum wire was left exposed. The platinum tip was cleansed of epoxy using a paper towel and left to dry for 24 hours.

At the end of the drying period, the dry tips were cleaned with a utility knife and rubbing alcohol, followed by a solution of 10% HCl and 10% detergent (Bailey and Beachamp, 1971). Tips were then rinsed with distilled water and capped with another plastic syringe tip, held in place by electrical tape. This protective cap was removed during installation.

The electrodes were checked by placing them in a standard redox solution (Zobell's solution) of 3.33mM potassium ferrocyanide, 3.33mM potassium ferricyanide and 0.1 M KCl (Farrell et.al. 1991) along with an Ag-AgCl reference electrode. A voltmeter was used to check the potential by connecting the terminals to the copper lead from the platinum electrode and the lead from the reference electrode. For reference purposes, the reference electrode lead was always connected to the common terminal of the voltage meter. With reference to an Ag/AgCl electrode, the voltmeter was expected to give a direct reading of +230 mV. All probes within ± 10 mV of this standard were rinsed with distilled water and recapped. Others were cleaned and checked again. The effect of differing lead length was also examined but had no affect on the electrode performance.

All instrumentation was connected to panel boards for easy access. The system installed allows in situ measurement of hydraulic head, temperature and oxidation/reduction potential, as well as the ability to retrieve water samples at 16 elevations within and below the liner of each cell (Locations 1 and 2) and 8 locations adjacent to each cell (Locations 3 and 4) (see Figure 2). The depths shown here for Locations 3 and 4 can be adjusted according to site sensitivities.

INSTALLATION

Installations were targeted for a location at least five meters into the bottom of the storage (L1), at the mid-point of the sidewall (L2), at high water level (L3) and four meters back from high water level (L4). At locations L1 and L2, bundles were installed at 0.0m (surface), 0.1m, 0.3m, 0.6m, 1.0m, 1.5m, 2.0m, and 3m depths. Bundles at location L3 and L4 were installed at 1m, 3m, 5m, and 7.5 m below high water level to coincide with installations at L1 and L2 (Figure 1). At L1, L2, L3, and L4 the bundles were installed at different depths approximately 1 m horizontally apart from each other as opposed to stacking the bundles. This ensures discrete sampling points. At each site several nested piezometers were installed at various distances up to 60 meters from the storage to measure groundwater mounding.

Test holes were completed with a churn rig mounted on a tandem axle truck and a continuous flight auger mounted on a compact loader. The deepest hole at each location was sampled continuously and the undisturbed samples taken to the laboratory for analysis. Each bundle (Figure 3) was installed in a 100-150 mm diametre hole, sand was place 50mm over the screened length, a 100 mm to 200 mm soil plug from the coinciding borehole and depth was compacted above the sand and the holes sealed to ground level with bentonite (Figure 2). Bundles at the 0.0, 0.1m and 0.3m levels were installed horizontally by hand, all others were vertical installations (Figure 4). Lines from all installations were laid in a 100 mm x 300 mm deep trench to a manhole, covered with bentonite powder and the trenches filled with compacted liner material (Figures 5 and 6). The goal of the line installations was to ensure no preferential flow to the instrumentation through the line trenches.

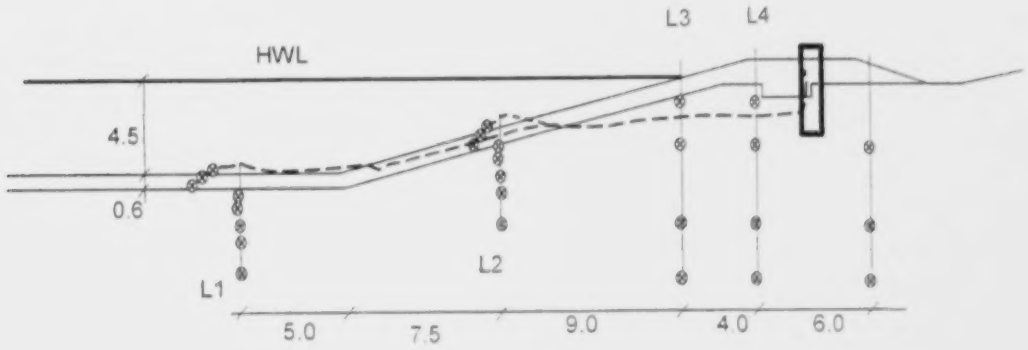

Figure 1. Location of instrument bundles installed in earthen manure storages

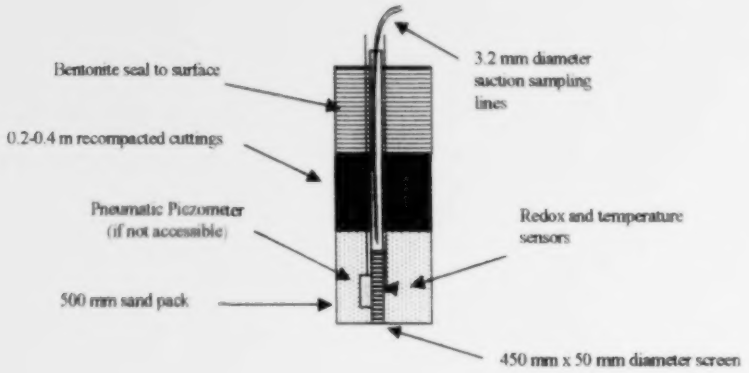

Figure 2. Sampling bundles for monitoring seepage from earthen manure storages.

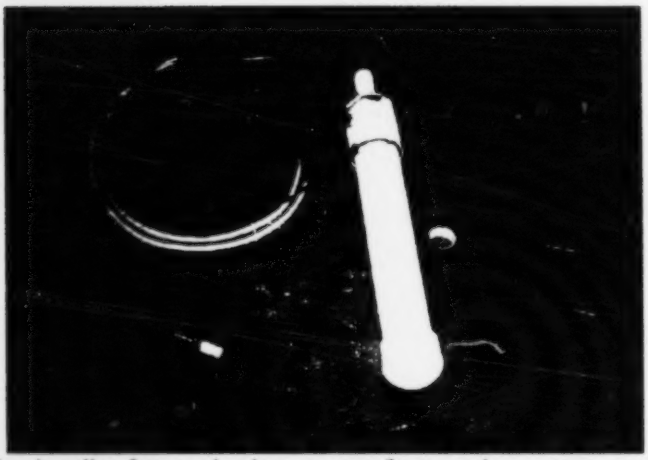

Figure 3. Sampling bundles for monitoring seepage from earthen manure storages

The instrument bundle shown in Figures 2 and 3 was placed in 16 locations underneath the EMS. When suction is applied to the sample tubing, a water sample can be retrieved for chemical analysis. The pneumatic piezometer provides the water head at the depth. The thermocouple allows temperature to be recorded, and the reduction-oxidation probe providing the redox conditions of the groundwater, which can help to speciate the groundwater chemistry.

Accessible piezometers are drilled at the 8 locations on the side and berm of the cell, therefore only the thermocouple and reduction-oxidation probes are necessary in these locations. After tips are in place, the holes are backfilled with 0.5-m of sand, 0.2 to 0.4-m of liner material, and bentonite chips to seal the hole.

Figure 4. Horizontal installation of tips at 0.1 and 0.3-m depths.

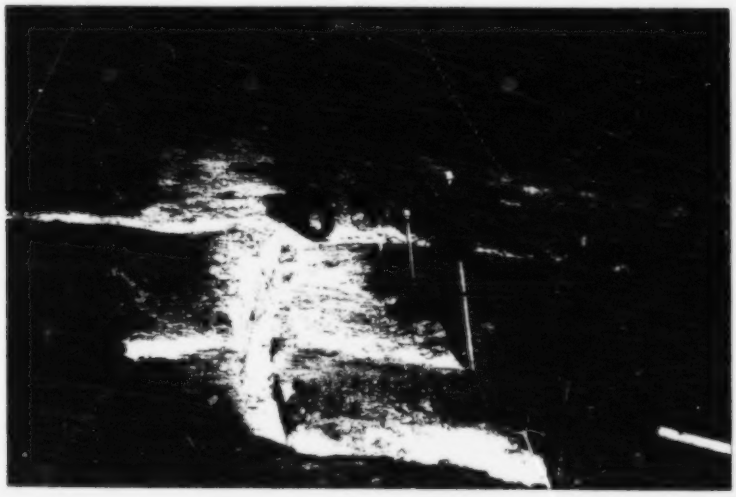

Figure 5. Laying instrumentation in trenches.

Figure 6. Instrumentation in manhole.

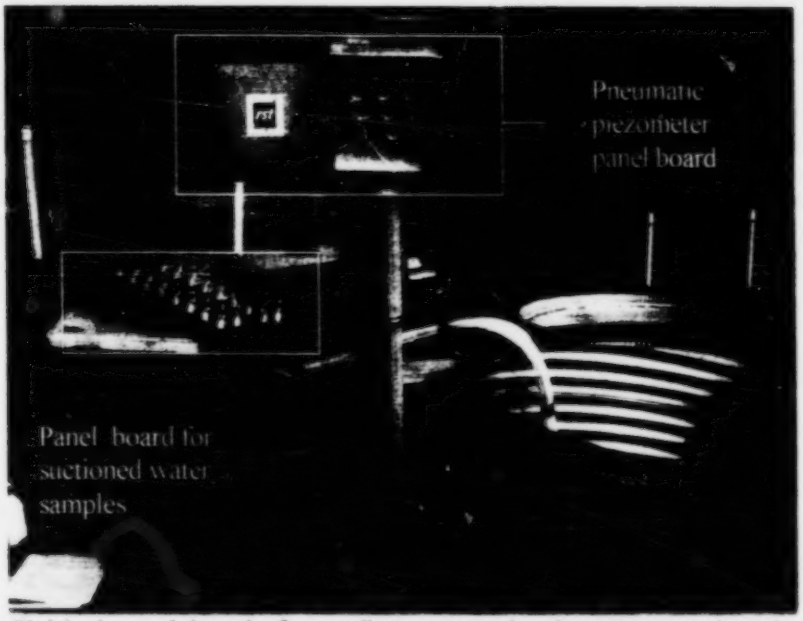

Figure 7. Finished panel boards for reading pneumatic piezometers and retrieving water samples.

SAMPLING AND ANALYSIS PROCEDURES

The water sampling instrumentation was connected to a panel board for easy access (Figure 7). Water levels beneath the storage cells are measured with a RST Digital Pneumatic Piezometer Reader. Water samples are obtained by placing suction on the 3.2mm lines until water flow is obtained. The water levels of standpipe piezometers are taken using a standard water meter tape. Water samples are taken from the piezometers using a jerk line. The water samples are stored in the refrigerator and analyzed for cations and anions using a Dionex ion chromatograph. Temperatures from the thermocouples are recorded with a lap top computer attached to a Campbell Scientific Data Logger. ORP probes are read in the same fashion with

the addition of a reference electrode placed in the liquid of the storage to adjust readings to the standard hydrogen electrode reference for ORP measurement.

Water Head Measurements Effects of the EMS cells on the groundwater hydrology of each site were monitored through the regular measurement of water levels in standpipe piezometers. Measurements were taken by lowering a measuring tape with a sound indicator at the tip into each piezometer. When the water surface is reached, the sound indicator beeps and the level to the water can be read from the tape. These measurements were subtracted from the surveyed levels of the standpipe rims and recorded as elevations.

Water head measurements were also taken by reading the pneumatic piezometers installed on the bottom and sides, and in some cases, around the earthern manure storages. The pneumatic measurements were read using a Pneumatic Readout model C-106 from RST Instruments. This instrument gave the readings in units of pressure, which were converted to a height of water and finally an elevation. Corrections are made for each pneumatic piezometer using equations formulated from calibration values received from RST Instruments.

In order to more directly determine the effects of the earthen manure storages on the water table, water levels were taken just prior to storage emptying, one week after emptying and approximately one month after emptying for the first year of monitoring. This was done at all sites when the storage cells were emptied for fall application. Currently, water levels are taken once a year when water samples are obtained.

Water Sampling and Field Analysis Water sampling was conducted twice a year during the first 2 years project to determine and quantify any solute movement that might occur. Since then, sampling has taken place once a year in the summer. Where possible, an initial sampling took place before the earthern manure storage facility was utilized in order to reveal any natural variations in groundwater solute concentrations.

Suction Sampling Samples were obtained from the Location 1 and 2 positions of the installation using the installed suction tubing. Shut off valves were installed on all lines. Initially, argon was attached to one of the two lines at a position, with a sampling container attached to the other. The purpose of the argon was to replace the void created by the removal of water and to allow minimal contact between the sample water and atmospheric air. This sampling container (Figure 3), a Nalgene reusable filter holder system (no. 301-500) from Fisher Scientific, was also attached to a controlled suction source. The suction source consisted of an electric pump attached to an empty propane tank fitted with a pressure gauge. The suction and argon sources were activated at the same time, causing water from the specific location beneath the storage to move up through the tubing and into the container, while argon was used to provide a slight pressure at the sampling tip to attempt to assist lifting the water sample to the container. The suction level was controlled by the valve on the propane tank and was kept at approximately –103kPa.

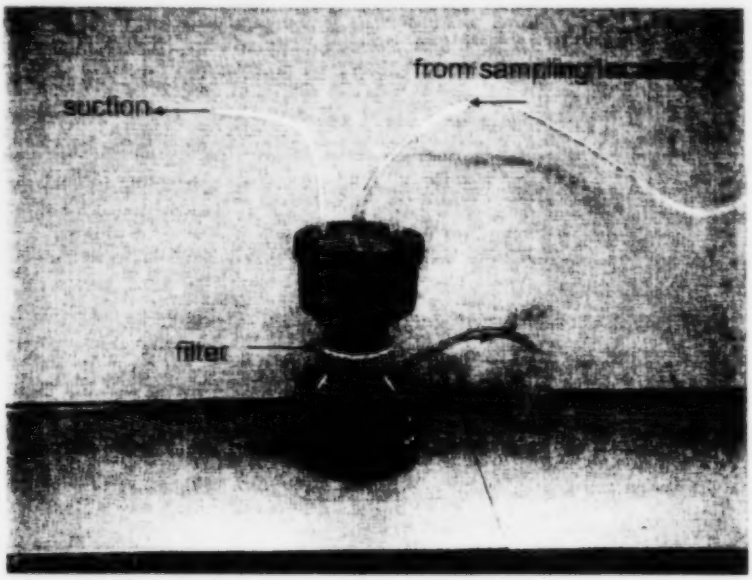

Figure 8. Suction sample container.

A new sampling method was used starting in the summer of 2002. The use of the argon to push the sampling through the tubing was eliminated. Only suction was used to draw the water sample into the sampling container. The argon was removed from the procedure because the water samples were exposed to atmospheric gases when being filtered and the use of the argon was unnecessary and did not appear to be helping to retrieve the sample.

After approximately 100 mL of water had been retrieved, the suction was halted and the water in the container removed. The suction was then continued until another 100mL of water had been retrieved. 100 mL is an adequate amount of water to remove all water from the longest suction line and is also adequate for alkalinity determination and sample analysis. The sampling line valves would be closed and the suction removed from the container. The sample was poured out of the sampling container into sterile containers.

Unfiltered water was used to perform electrical conductivity, temperature, and pH readings. pH measurement was taken using a handheld pH meter. The remainder of the water was filtered using a syringe and a filter holder with a 45µm sterile filter. Of this filtered sample, 20mL was used to obtain an alkalinity value with the remainder divided between two sterile test tubes. Field alkalinity measurements were determined using endpoint titration with a HACH field alkalinity kit. One of the tube samples was acidified and both tube samples were kept cool until laboratory analysis. If possible, these containers were overfilled with water to allow minimal oxygen contact. Due to limited water available at some positions, this was not always possible.

Standpipe Sampling Water samples from standpipe piezometers were retrieved using a length of 3.2mm diameter tubing equipped with a check valve (jerk line). Removing excessive amounts of water could have induced seepage or effected ground water mounds due to the sensitivity of the hydraulic conditions at these sites; therefore, small amounts of water

were to be removed. Minimal removal of water from standpipes during sample collection was required but a representative sample was also required.

The line was dropped to the bottom of the hole and then lifted to a level of 0.5m above the bottom. Approximately 100-200mL of water was then purged from the pipe before sample collection. This jerk line provided low rate of purging, as well as minimal water volume removal as desired. The same field analysis and filtration techniques were performed on these samples as were performed on the suction samples. A standing water column of at least 1.5m is recommended if this sampling method is to be used to minimize affects of oxygen diffusion. If there is less than 1.5m of standing water and the installation is in low permeability material, a packer could be placed in the piezometer above the water level.

ORP Readings Redox readings were taken by connecting the redox probes to a dataTaker 100 data logger. A reference electrode of a known potential (Ag/AgCl or calomel) was also connected to the data logger and placed in a saturated area on the side of the EMS effectively creating a "battery" situation of a voltage difference between points of different potentials. Voltage readings were taken between the ORP probe and the reference electrode every ten seconds for a total of ten minutes to allow the readings to stabilize (Bailey and Beauchamp, 1971; Rickman et al.; 1968).

Temperature readings were taken every ten seconds for a total of five minutes. The thermocouples were connected to an iso-block, which was connected to the data logger. Average values were used in analysis. These readings were taken at the same time as the water levels at each site.

Laboratory Water Analysis The water samples from each site were analyzed using an ion chromatograph Dionex model DX-320 with Chromeleon software at the University of Saskatchewan Department of Geological Engineering. Water samples assessed using the ion chromatograph were analyzed for both cations and anions. Cation analysis included sodium, ammonium, potassium, magnesium, and calcium. Anion analysis consisted of chloride, nitrite, nitrate, and sulphate.

The samples were prepared for the Dionex by storing the water samples in a refrigerated environment of approximately 1-5°C until they were ready to be diluted. The cation samples were acidified with one drop of hydrochloric acid to every 100 mL of sample retrieval at the time.

Volumetric flasks of various sizes are used in the dilution procedure. The volumetric flasks were cleaned by rinsing with deionized water and sterilizing in the oven for two hours at 160°C. Once removed from the oven, the volumetric flasks were rinsed twice with distilled water and once with deionized water. They were filled ¼ full of deionized water and 1mL of sample was injected into the flask with a pipette. The volumetric flask containing the sample was then filled with deionized water, covered, and inverted ten times. The Dionex sample bottle is rinsed with the dilution in the volumetric flask before being filled. The Dionex sample bottles were stored in the fridge at 1-5°C until they were analyzed.

RESULTS

Groundwater mounds have developed in the vicinity of all three newly constructed EMS constructed in clay and/or clay till material. An example of this is shown in Figure 9. These mounds do not dissipate upon emptying of the storages and, in some cases, induce discharge heads in the empty secondary cell.

The groundwater samples indicate that seepage has resulted in elevated ion levels (ion concentrations greater than 10 meq/L) to depths of up to 1.5 meters below some of the storage cells and to distances of up to 10 meters directly out from the toe of the inside slope of the EMS since their commissioning between 1998 and 1999. Seepage is most evident at storage cells that were either empty for one season prior to use (allowing liner to dry up and crack) or where liner damage occurred. Figures 10 and 11 shows an example of the electrical conductivity profiles and Eh profiles of the water samples taken at Site C, Cell No. 1, respectively.

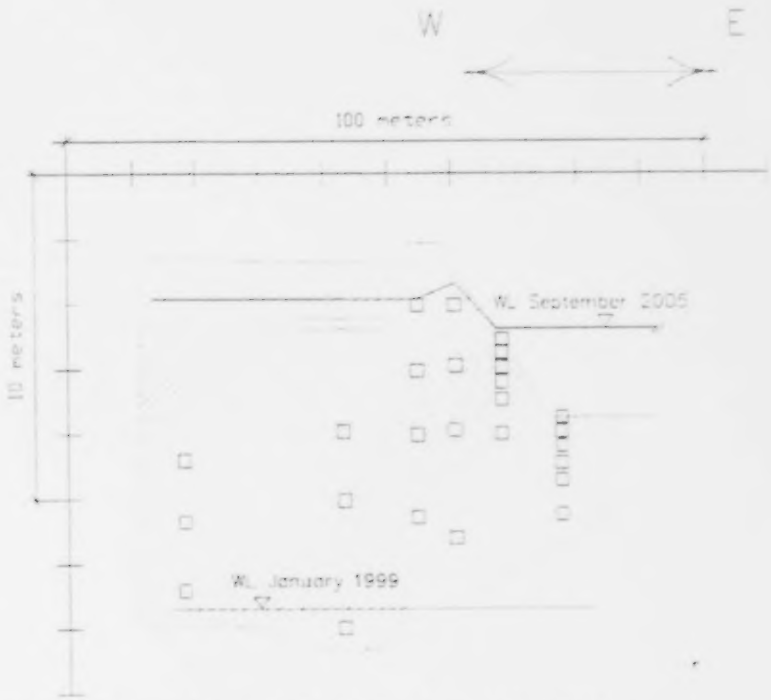

Figure 9. Groundwater levels at Site C, Cell No. 1 from 1999 to 2004.

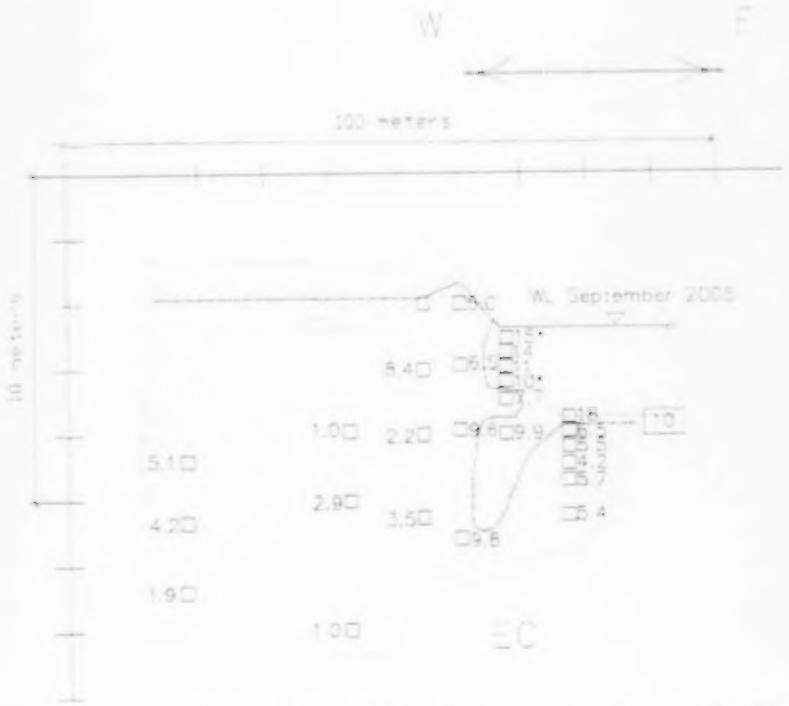

Figure 10. Electrical conductivity (mS/cm) of groundwater taken at Site C, Cell No. 1 in 2005.

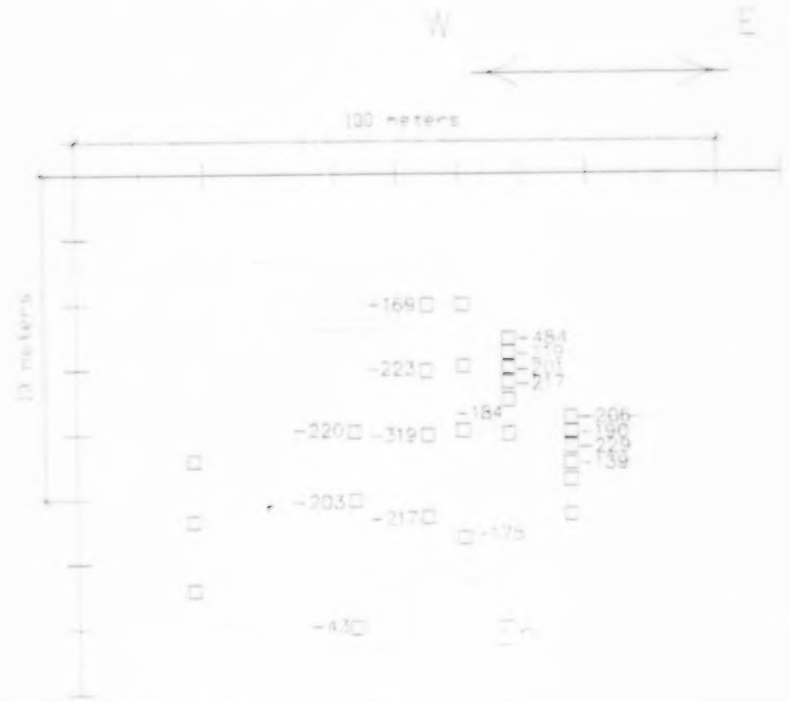

Figure 11. Eh readings (mV) at Site C, Cell No. 1 in 2002.

CONCLUSIONS

Groundwater chemistry at four EMS sites was studied for a period of six years. Three of the sites (A, B, and C) had similar monitoring systems installed as the storage was being constructed. The fourth site (No. 1) was an existing EMS and unique monitoring equipment was installed as such. Sites A, B, and C have two earthen manure storages at each site, Cell 1 (solids) and Cell 2 (liquid).

All three, newly constructed EMS sites developed groundwater mounds after filling. The maximum mound elevation appears to reflect the high water level of the storage. The mounds did not appear to dissipate when the storage is emptied causing groundwater discharge heads in Cell 2 of the storage for several months of the year.

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Long Term Monitoring Results from Three Earthen Manure Storages in Saskatchewan

Paper No. 3

ADF Project # 20000265

Report Submitted to:
Agricultural Development Fund
Saskatchewan Agriculture and Food

Prepared by:

T. A. Fonstad, Ph.D., P.Eng. and Crystal Rinas, B.E.
Department of Agricultural and Bioresource Engineering
University of Saskatchewan

May 2006

ABSTRACT

Groundwater monitoring systems were installed at three newly constructed earthen manure storage (EMS) sites. Groundwater levels and chemistry was monitored from 2001 to 2005. Elevated ion concentrations of greater then ten milliequivalents per litre (meq/L) were used to determine the extent of seepage from the EMS. Seepage extends to depths of up to 1.5 m below the EMS and up to 10 m parallel to the toe of the inside slope of some of the EMS sites. Ammonium and potassium ions appear to be attenuated with respect to chloride. The EMS that have the greatest extent of seepage have experienced liner damage in the past.

INTRODUCTION

The main objectives of this project were to set up a monitoring program to provide data regarding the long term performance and safety of earthen hog manure storages. To reach this objective, it was necessary to monitor newly constructed storages, but also to complete detailed investigations of an existing older storage and set up laboratory experiments to help understand the processes affecting the rate of seepage from the storages. The data collected from this project should increase public assurance and investor confidence in the hog industry. Results will also confirm the role of liners in new storages, the site characteristics required for establishment of new storages and possible requirements for decommissioning.

This paper will look at the results of groundwater data collected from seepage monitoring systems at three newly constructed EMS sites. Monitoring systems were installed in three new sites from 1998 to 1999. The new sites are referred to as Site A, an engineered two-cell EMS constructed in clay soils that services a 600 sow farrow to finish swine barn. Site B, an engineered two-cell EMS constructed in a layered sandy till soils that services a 10,000 head hog finishing barn and Site C, an engineered two-cell EMS constructed in till soils that services a 1200 sow farrow to finish swine barn. Groundwater chemical data was collected annually at the three sites from 2001 to 2005.

BACKGROUND

EMS Seepage Monitoring

Seepage losses from EMS have been a concern in North America since at least the early 1960's. Initial studies focused on quantifying seepage losses so appropriate regulations could be developed for new EMS (Hart and Turner 1965; Davis et al. 1973; Chang et al. 1974; Lo 1977; DeTar 1977). During these investigations clogging of soil pores by particulate matter was found to significantly reduce the quantity of effluent leaving an EMS by seepage. Studies into the mechanisms of soil clogging and the ability to rely on soil clogging to permanently reduce seepage losses continued until the late 1990's (Fonstad 1996; Maule and Fonstad 2000).

Other research has focused on delineating leachate plumes at livestock production sites. Soil coring, monitoring well installations and remote sensing have all be utilized to attempt to determine the extent of plumes.

The measurement of groundwater quality through monitoring wells is a method commonly used to monitor EMS seepage (Parker et al. 1999). The extent of seepage determined through installation of shallow monitoring wells has been undertaken in various locations in the United States of America and Canada. Westerman et al. (1993) reported nitrogen within the manure storage present as ammonium. Effluent samples from the plume indicated as much as 50% of the nitrogen was present as nitrate; this prevalence is expected as ground waters of the surficial sands in the North Carolina site have warm temperatures (near 20°C) and contain high levels of dissolved oxygen, both of which promote microbial conversion of ammonium to nitrate. Ciravolo et al. (1979) recorded ammonium and nitrate near the EMS and nitrification near the front of the plume at both locations they studied. These results may be due to warm temperatures and high dissolved oxygen levels in the shallow groundwaters of the Mid-Eastern United States where the study took place.

Plumes from EMS in the Canadian Prairies do not appear to have nitrogen present as nitrate, possibly due to lower groundwater temperatures (6 °C) and low dissolved oxygen levels inhibiting microbial conversion (Fonstad 2004).

Additional methods used to detect EMS seepage (soil sampling, redox conditions, and electromagnetic surveys) are reviewed in detail in Fonstad and Rinas (2006). The result of this review demonstrated the need for investigations to determine EMS effluent chemistry, transport mechanisms and plume characterization. This need led to the design and implementation of a groundwater monitoring system for earthen manure storages.

Geochemical Conditions within an EMS Effluent Plume

In order to understand the mechanisms controlling the species of concern within an EMS effluent plume, the following background information on nitrogen transport, redox conditions and cation exchange is provided.

Nitrogen transport Nitrogen is subject to many possible transformations as it is leached through the soil. These transformations depend on conditions at the site. It could be adsorbed into the soil matrix, oxidized or reduced, or even assimilated into the soil biomass.

Nitrogen can occur in different oxidation states from –3 (NH_3 and NH_4^+) to +5 (NO_3^-). Many of the transformations between states are carried out by microorganisms at normal temperatures and pressures (Paul and Clark 1996). For example, nitrogen is present in anaerobic waste storages, on exchange sites in the clay lattice, and in many fertilizers in the ammonia (NH_3) or ammonium (NH_4^+ or N(-3)) state, while nitrate (N(5)) is present in the aerobic zone of surface soils and in some fertilizers.

The positive charge on the ammonium ion leads to ammonium adsorption to clays and organic matter. NH_4^+ is held on the exchange complex where it can be replaced by cations from the soil solution.

NH_4^+ can be oxidized to NO_3^- by chemoautotropic bacteria if oxygen levels are sufficient. This process in known as nitrification and is shown below:

$$\underset{-3}{NH_4^+} \longrightarrow \underset{-1}{NH_2OH} \longrightarrow \underset{+1}{NOH} \longrightarrow \underset{+3}{NO_2^-} \longrightarrow \underset{+5}{NO_3^-}$$

Once ammonium is converted to nitrate, the nitrogen has a negative charge and becomes an unattenuated ion and cannot be adsorbed on to negative soil exchange sites.

Redox conditions The issues of concern when storing animal manure in EMS are large quantities of organic matter and relatively high concentrations of nitrogen. Any plume which develops will likely experience reducing conditions and ion exchange; both factors are significant in regards to the transport of nitrogen in the effluent plume. If ammonium seeps from the EMS into a reducing environment, it will tend to stay as ammonium and be subject to ion exchange. This will lead to attenuation of nitrogen in the effluent plume and may provide for some protection against nitrogen contamination of nearby aquifers. An understanding of redox zoning and adsorption processes will aid in the interpretation of investigations of transport mechanisms of EMS effluent.

Cation exchange Ion exchange has an effect on plume development and geochemistry. In the case of EMS leachate plumes there are often many contaminant species involved When several species are present, complex breakthrough patterns can occur as the plume progresses (Vulava et al. 2002; Voegelin et al. 2000). These complex breakthrough patterns occur due to the competitive adsorption of cations. Certain cations are preferred on the soil exchange sites. This preference is based on (Fonstad 2004):

- the charge of the ions;
- the size of the ion or hydrated radius;
- the properties of the exchanger (e.g. clay mineral);
- quantity and ratios of the various valence of ions present; and
- the total solution concentration.

Cations that are adsorbed by the soil do not appear in the plume as rapidly as unreactive anions such as chloride. This presents a separation of the ions as they appear in the plume known as a chromatographic sequence.

SITE CHARACTERIZATION AND INSTALLATION

Site A

Site Description Site A is a 600 sow farrow-to-finish research and production unit that is serviced by an engineered two-cell EMS providing 400 days of effluent storage. A 600 mm thick recompacted clay liner was placed on the bottom of the storage with one metre thick liner built on the sides. Liner construction was performed as per recommendations by consulting engineers.

Site Background The land surface at this site is defined as moderately rolling to undulating with glacial lacustrine - alluvial plains. Examination of an aerial photograph of the area reveals a surface with many potholes, indicating poor surface drainage. The property is located in the Saskatchewan Rivers Plain physiographic region. Surficial soil is characterized as variable textured lacustrine and alluvial sands, silts and clays. The upper 30 to 40 m of this site consists of glacial till and stratified drift. This is underlain by 30 to 50 m of the Bearpaw formation (non-calcareous silty clay shale), followed by 20 to 30 m of the Judith River formation (non-calcareous sand, silt and clay) and 270 m of the Lea Park Formation - Upper Colorado Group (silty clay-shale).

The initial site investigation at this site was performed by P. Machibroda Engineering, Ltd. Drill logs from test holes at the EMS site showed 200 to 250 mm organic topsoil followed by medium to highly plastic clay to a depth of 5.5 to 7.6 m below grade. This was underlain by glacial till which extended the depth of exploration (15.1 m below ground surface).

The upper soils have clay contents from 37% to 57%, 93% to 100% fines, and a plasticity index of 21% to 46%. Values for the lower till zone are all lower than this, with 18% to 39% clay, 62% to 94% fines, and a plasticity index of 10% to 14%. Based on these values, the bulk hydraulic conductivity is estimated at 10^{-9} to 10^{-8} cm/s. Standard Proctor moisture density and cation exchange capacity was determined for soil at two depths in test hole 10 (see Table 1).

Table 1. Soil laboratory analysis.

Test Hole No.	Depth (m)	Cation Exchange Capacity (meq/100g)	Standard Proctor - Moisture Density			
			Optimum Moisture (%)	Dry Density (kg/m^3)	Void Ratio	Porosity (%)
10	2.0-4.5	18.7	24.3	1558	0.82	45
10	5.5-7.0	22.1	26.4	1515	0.85	46

Groundwater is encountered within and above the glacial till strata of this site. The upper groundwater table is phreatic, found 5 to 12 m below original ground surface. Two wells within 1.6 km of the property were found in Saskatchewan Water Corporation Records. These wells were completed at 21.9 and 36.6 m below ground, both with pumping rates

of 45 litres per minute. An additional well was reported within the range of 1.6 to 3.2 km of the site, with a completion depth of 38.1 m.

The primary source of water, both human and agricultural, in this region is the groundwater. Therefore, the EMS, as a potential source of contamination, should be monitored for plume formation and migration.

Chronology of Events Liner construction and monitoring system installation was completed during November of 1999. Installation was completed following the methodology presented in Fonstad and Rinas (2006) and the layout is shown in Figures 1 to 3. The automated reading systems for redox and temperature instruments, as well as the boards for pneumatic piezometres and water sample tubing were installed in spring 2000. Additional drilling was conducted by Prairie Farm Rehabilitation Administration (PFRA) and University of Saskatchewan in October of 2000. Standpipe piezometres and pneumatic piezometres were installed at several locations surrounding the EMS storages.

After installation, the groundwater samples were analyzed annually from 2001 to 2005.

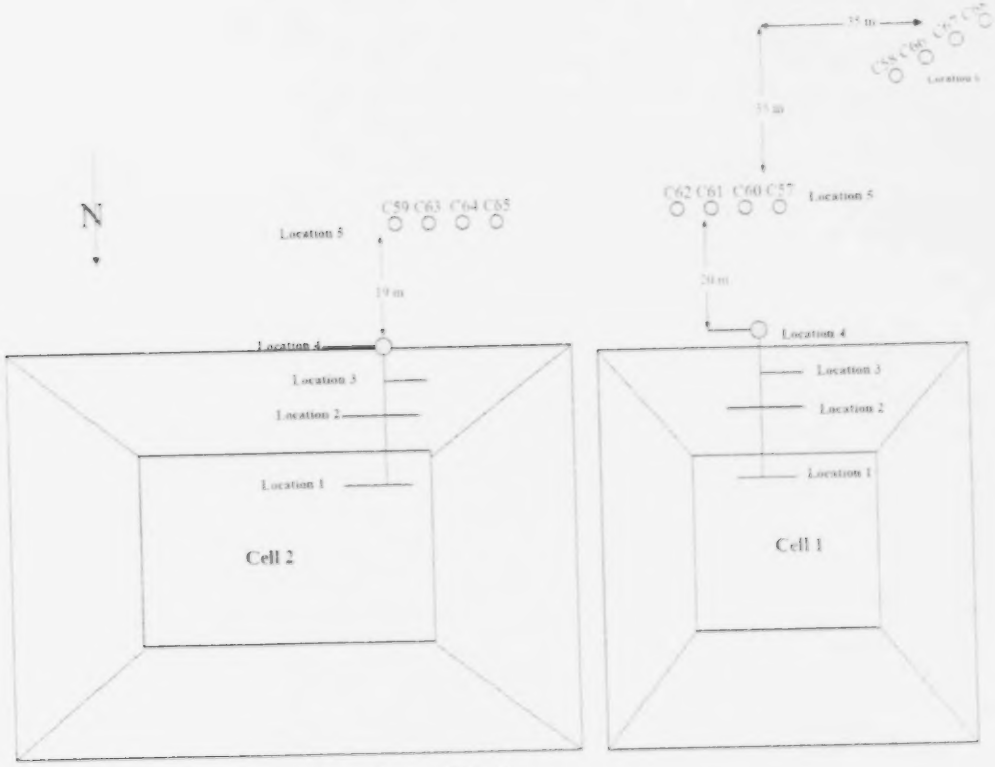

Figure 1. Monitoring system location at Site A.

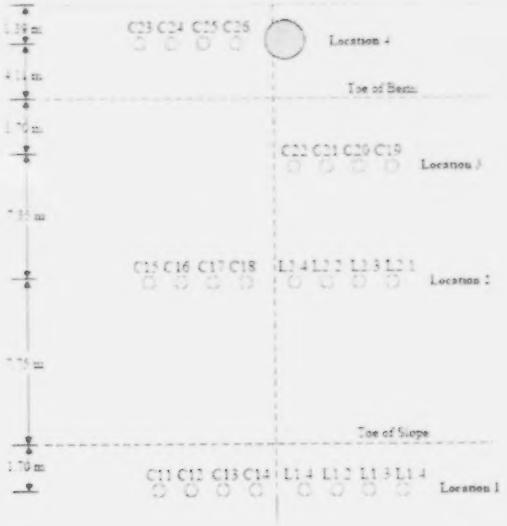

Figure 2. Locations 1, 2, 3 and 4 at Cell No. 1, Site A.

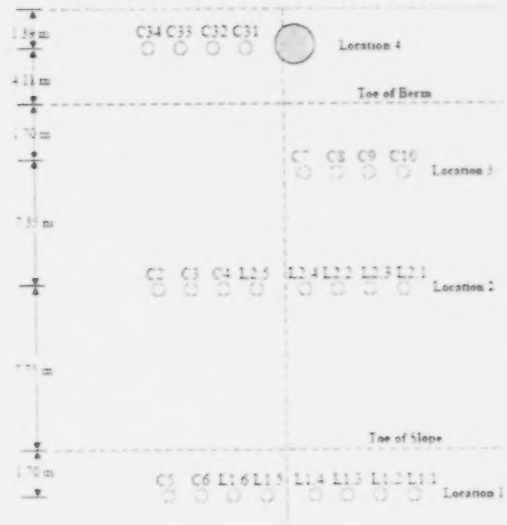
C34 C33 C32 C31
Location 4
Toe of Berm
C7 C8 C9 C10
Location 3
C2 C3 C4 L2 5
L2 4 L2 2 L2 3 L2 1
Location 2
Toe of Slope
C5 C6 L1 6 L1 5
L1 4 L1 3 L1 2 L1 1
Location 1

Figure 3. Locations 1, 2, 3 and 4 at Cell No. 2, Site A.

Site B

Site Description Site B is a 10,000 head hog finishing barn serviced by an engineered two-cell EMS facility with a capacity for 400 days of effluent storage. The storages were constructed during the summer of 1998.

Site Background This site is located on the northern fringe of the Quill Lake Plain. This physiographic region is characterized by the presence of glacial till and glaciofluvial plains. The topography is gently undulating to rolling. The top 60 m at this site consist of glacial till and stratified drift underlain by approximately 180 m of bedrock from the Riding Mountain Formation. This formation is non-calcareous silty clay, with fine sand interbedded within the top 60 m.

A subsurface soils investigation was conducted by P. Machibroda Engineering at this site in Spring of 1996. Drill logs at this site show 100 to 150 mm of organic topsoil followed by clay or glacial till. Any clay encountered ran to a depth of 0.4 to 1.8 m below grade and was underlain by glacial till. Glacial till was encountered to the bottom of all test holes (6.1 to 13.0 m). Silt and sand lenses were encountered at various depths throughout the till. Cobblestones and boulders were also found.

The till at this site was found to have a clay content of 21 to 34% and a fines percentage of 56 to 99%. A rising head response test performed on Test Hole 12A showed a bulk saturated hydraulic conductivity of 1.3 x 10^{-6} cm/s. See Table 2 for more results of soil laboratory analysis.

Table 2. Soil laboratory analysis.

Test Hole No.	Depth (m)	Cation Exchange Capacity (meq/100g)	Standard Proctor - Moisture Density			
			Moisture Content (%)	Dry Density (kg/m^3)	Void Ratio	Porosity (%)
12A	0-5.0	14.4	13.2	1870	0.47	32

Multiple groundwater systems exist above and below the glacial till at this site. The top system is a phreatic groundwater table occurring 3.0 to 6.0 m below existing grade. This is a low yielding, highly mineralized system. Water is also encountered within the sand and gravel deposits located throughout the till.

Groundwater supplies both human and agricultural requirements in this area. Saskatchewan Water Corporation has record of six water wells within 1600 m of this site. Four of these wells were producing wells, with recorded yields of 1.1 to 1.9 L/s. Depths ranged from 24.4 to 65.5 m below grade. The fifth well was drilled to a depth of 7.3 m with no yield reported and the sixth was a test boring that reported clay throughout the entire drill depth.

Saskatchewan Agriculture and Food suggests that the bottom elevation of an EMS should be a minimum of 1m above the level of the static water table. Due to the this requirement,

the level of the water table at this site, as well as the dependence on groundwater in this area, a groundwater system installed in the EMS liner to ensure its effective long-term performance was suggested.

In situ soils at this site do have a moderate clay content, which will help to retard movement of seepage from the EMS, but they also possess a relatively low cation exchange capacity (CEC). This low CEC indicates that the natural attenuation rate of nutrients introduced to the ground system will be slow. This information contributed to the decision to include a groundwater monitoring system in the EMS.

Chronology of Events Liner construction was completed during June of 1998. During June and July 1998, the monitoring system was installed in Cell 1 and Cell 2 by PFRA and the University of Saskatchewan.

During the summer of 1999, liquid from the EMS was found to be accumulating in the manholes installed with the monitoring systems the previous year. It was determined that the deep trench dug to carry the instrumentation into the bottom of the 3m deep manholes was leaking. As a solution, the trench was reopened, sealed with bentonite powder and recompacted. Also, concrete was poured into the manholes to seal the opening of the trench and prevent any further leaking. Due to this problem, the design of the system was altered to allow for a shallower manhole installation.

On June 20, 1999, a pin connector was placed on all thermocouples and another was placed on all redox probes in the manhole. These probes can now be read much faster by using the pin connectors to hook the probes to a datalogger, which can then be read by a computer. Pneumatic piezometres and water tubings were each connected to boards to ease data collection.

Additional holes were drilled on July 5 to 7 and again on August 26 to 31 of 1999 by PFRA and University of Saskatchewan. Standpipe piezometres were installed in 17 of these, with pneumatic piezometres placed in two. These additional piezometres were placed around the primary cell to more closely monitor observed groundwater mounding. The location of sampling points are shown in Figures 4 to 6.

The groundwater at all Site B locations were sampled annually from 2001 to 2005.

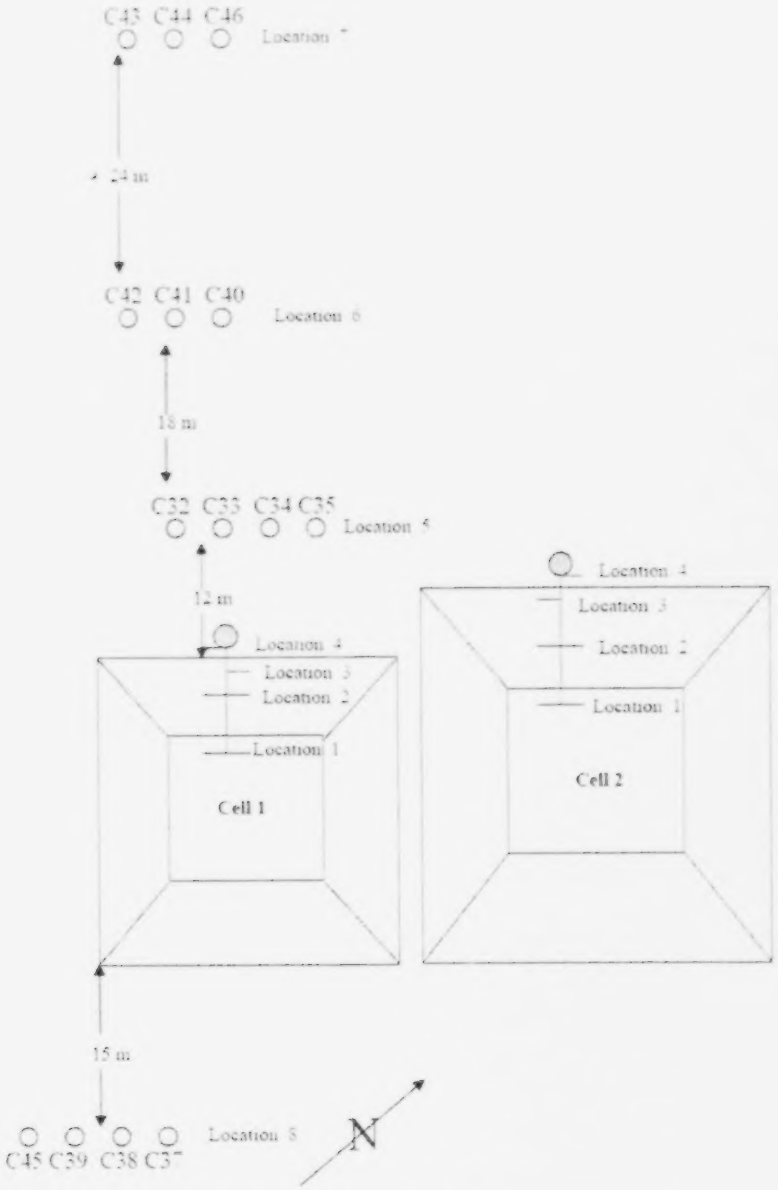

Figure 4. Monitoring system location at Site B.

Figure 5. Locations 1, 2, 3 and 4 at Cell No. 1, Site B.

C1 C2 C3 C4
Location 4
Toe of Berm
C17 C16 C15 C14
Location 3
C13 C12 C11 C10 L2 5 L2 6 L2 7 L2 8
Location 2
Toe of Slope
L1 8 L1 7 L1 6 C5 C6 C7 C8 C9
Location 1

Figure 6. Locations 1, 2, 3 and 4 at Cell No. 2, Site B.

Site C

Site description Site C is a 1200 sow nucleus unit serviced by an engineered two-cell EMS constructed to provide 400 days of effluent storage.

Topsoil was stripped from the surface before storage construction was begun. After digging out the storage depth, the clay till present at the site was compacted into a 600 mm thick liner in the storage. Liner construction was performed as per standards recommended by the consulting engineers.

Background information The property is situated within the physiographic region Touchwood Hills Upland. This is characterized by rolling morainic plains and till plains with moderately undulating to strongly rolling topography. The upper 200 m consists of glacial till and stratified drift followed by approximately 150 m of silty clay-shale of the Lea Park Formation - Upper Colorado Group

Test drilling was done at this site by P. Machibroda Engineering Ltd. to determine any environmentally sensitive aspects of the area. The site was found to have 300 to 400mm of topsoil, underneath which was a layer of variable lacustrine and alluvial sands and clays extending to depths of 0.8 to 1.0 m below ground surface. Beneath this is two till layers. The upper till layer is oxidized to a depth of five to seven metres with the lower one to three metres unoxidized. The lower till strata was of similar characteristics to the upper till and continued to a least 11.2 m below grade, oxidized to the depth of exploration. At the till contact a discontinuous sand lens ranging from 0.0 to 1.5 m in thickness was encountered.

The glacial clay till at this site was determined to have 22% to 31% clay content, 56% to 63% fines, and a Plasticity Index of 12% to 16%. A rising head test performed on test hole 98-3 indicated a bulk saturated hydraulic conductivity of 4.4 x 10^{-5} cm/s. More information on the soil characteristics at this site is presented in Table 3.

Table 3. Soil laboratory analysis.

Test Hole No.	Depth (m)	Cation Exchange Capacity (meq/100g)	Standard Proctor - Moisture Density			
			Optimum Moisture (%)	Dry Density (kg/m^3)	Void Ratio	Porosity (%)
98-2	4.5-6.0	10.3	11.9	1911	0.44	31

The static water table is approximately five to eight metres below ground level, with flow in a east/ southeast direction at a gradient of 0.001. A downward hydraulic gradient was also noted, indicating a groundwater recharge area.

Due to the presence of the sand layer between the two till layers and the possibility of contamination, it was necessary to put a monitoring system into this site to obtain the permit.

Chronology of Events Liner construction and monitoring system installation was completed in July of 1999. Two SSRI/AEP tests were performed on the bottom liner of each cell. The position of pneumatic and standpipe piezometres are shown in Figures 7 to 9.

Installation for this and Sites A and B was performed in a manner similar to the installation method followed in Fonstad and Rinas (2006).

Groundwater at this site was sampled and analyzed annually from 2001 to 2005.

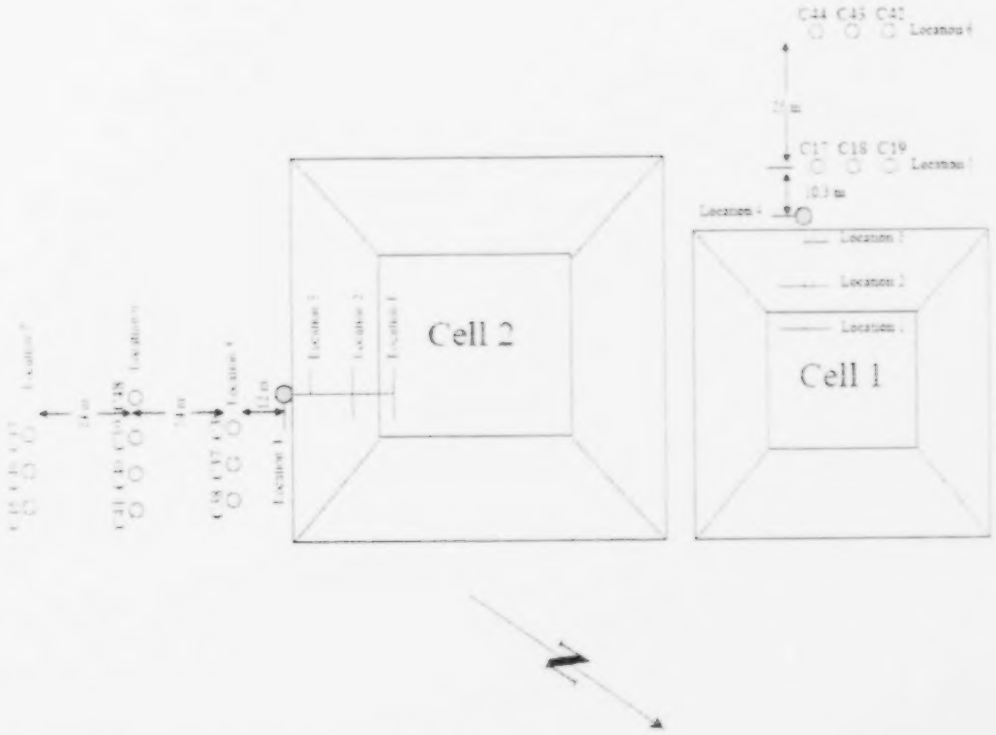

Figure 7. Monitoring system location at Site C.

Figure 8. Locations 1, 2, 3 and 4 at Cell No. 1, Site C.

Figure 9. Locations 1, 2, 3 and 4 at Cell No. 2, Site C.

METHODS AND MATERIALS

Water levels and pressures were recorded at all locations to determine gradients and water table levels. Water samples were obtained with a jerk line (6 mm polyethylene line with a check valve on the bottom) from all standpipe installations at the three sites. Water samples beneath the storage cells are obtained by placing suction on the 3.2 mm lines until water flow is obtained.

Water sample analysis included field determination of pH, alkalinity, temperature and electrical conductivity (EC). From 2001 to 2003, the field filtered water samples were stored at 5 °C in a refrigerator and analyzed for calcium, magnesium, sodium, potassium, chloride, sulphate, ammonium and nitrate plus nitrite using a Dionex ion chromatograph. In 2004 and 2005, the water samples stored at approximately 5 °C were submitted to the Saskatchewan Research Council Analytical Laboratory in Saskatoon within 24 hours for analysis of calcium, magnesium, sodium, potassium, chloride, sulphate and ammonium. These constituents plus bicarbonate (as determined by field alkalinity) were assumed to be the major ions present in the samples.

For a more detailed explanation of all methods and materials used for sampling and analysis procedures, refer to Fonstad and Rinas (2006).

RESULTS AND DISCUSSION

All three EMS sites have developed groundwater mounds (Figures 10 to 15). The maximum mound elevation appears to reflect the high water level of the storage. The mounds do not appear to dissipate when the storage is emptied causing groundwater discharge heads in Cell No. 2 of the storages for several months of the year.

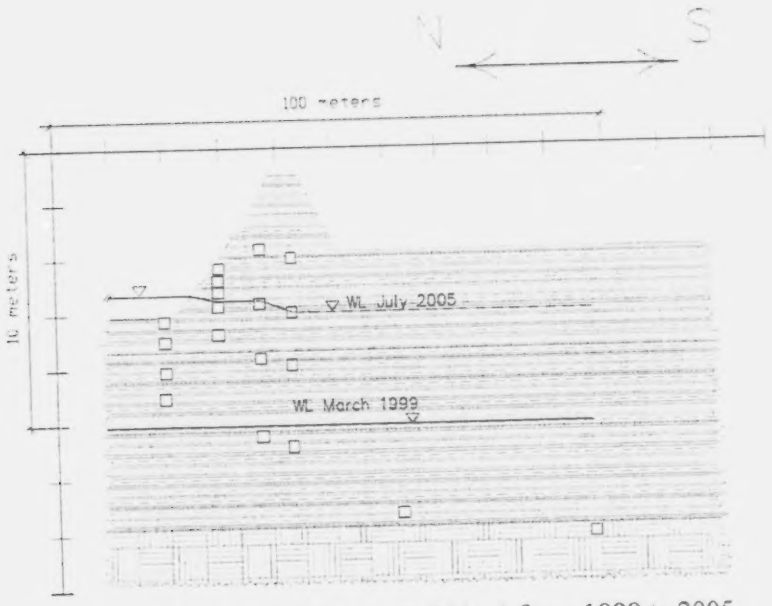

Figure 10. Groundwater levels from Site A, Cell No. 1 from 1999 to 2005.

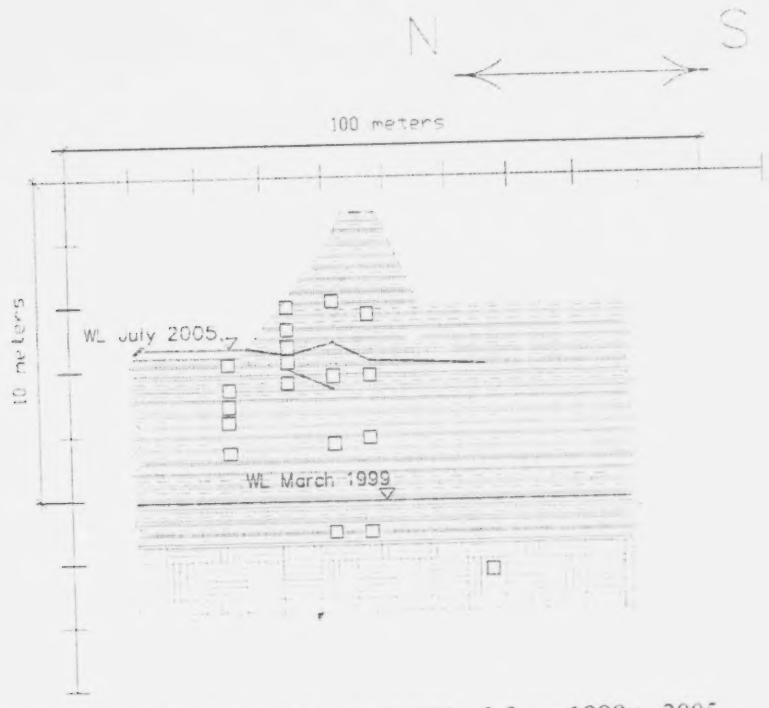

Figure 11. Groundwater levels from Site A, Cell No. 2 from 1999 to 2005.

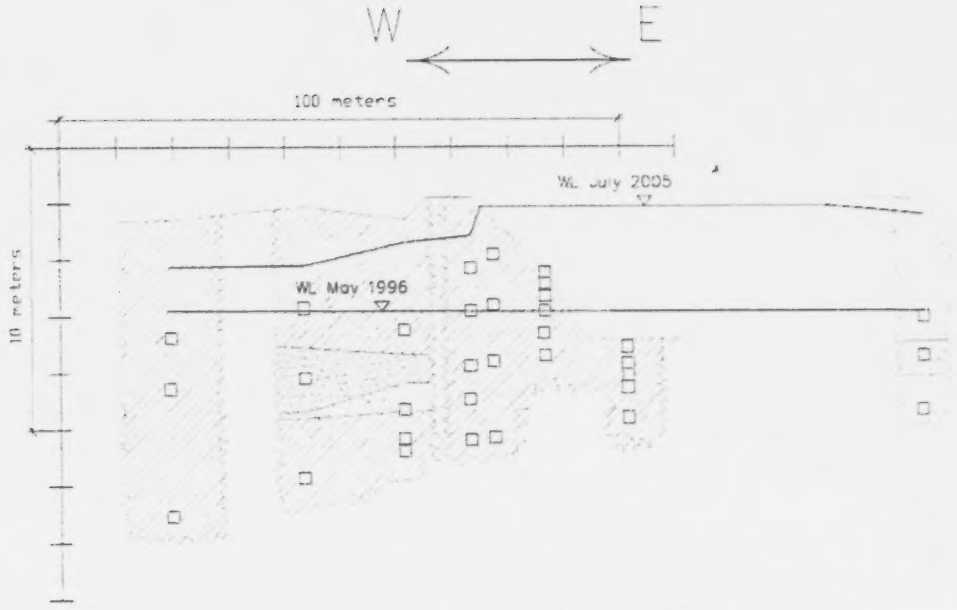

Figure 12. Groundwater levels from Site B, Cell No. 1 from 1996 to 2005.

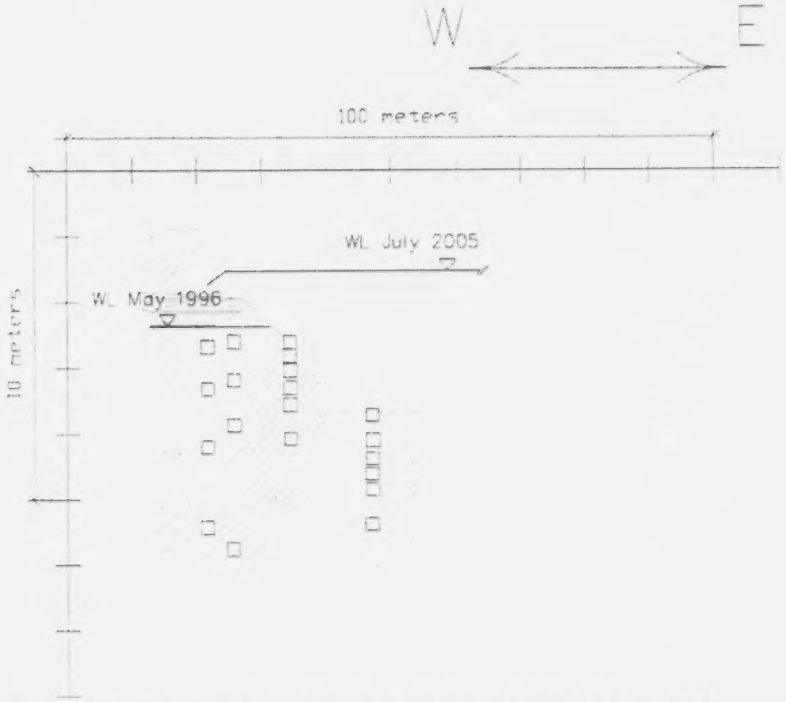

Figure 13. Groundwater levels from Site B, Cell No. 2 from 1996 to 2005.

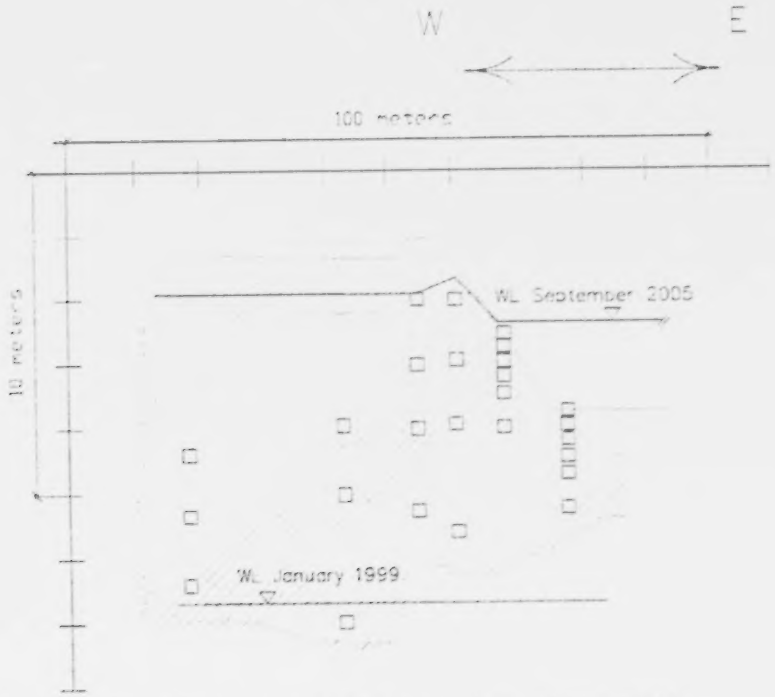

Figure 14. Groundwater levels at Site C. Cell No. 1 from 1999 to 2004.

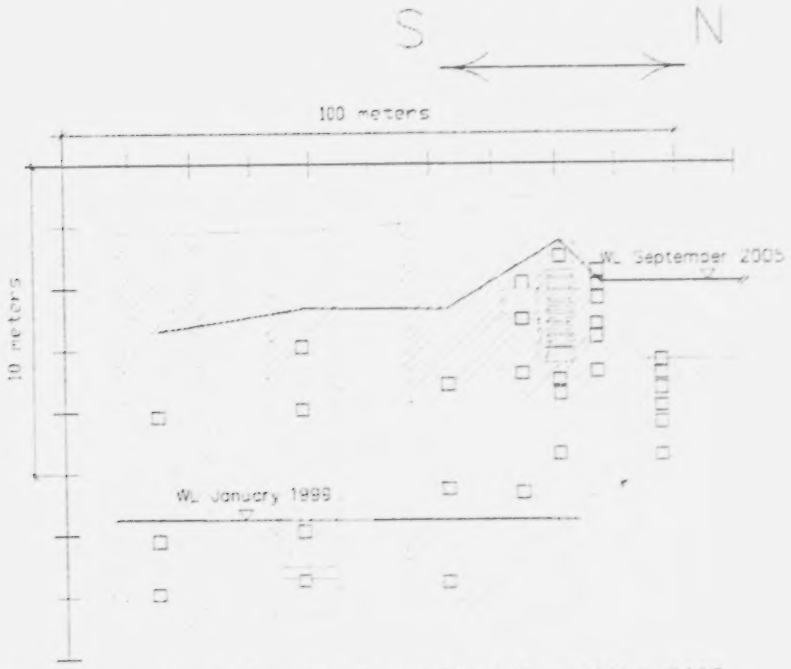

Figure 15. Groundwater levels from Site C. Cell No. 2 from 1999 to 2005.

Site A

Figures 16 to 55 show geologic sections of the site with concentration profiles for electrical conductivity, chloride, alkalinity, ammonium, potassium, magnesium, calcium, sodium, sulphate and pH in June 2001 and July 2005.

2005 electrical conductivity readings from the monitoring system installed below and adjacent to Cell No. 1 indicate elevated total dissolved solids (TDS) concentrations (TDS is approximately equal to 0.65 x EC, (Freeze and Cherry 1979)) to depths of over 3 metres and approximately 23 to 25 metres south of the toe of the inside side slope of the storage. These elevated ions concentrations in the pore water solution appear to be the result of EMS seepage near the storage and ion exchange and mineral dissolution at greater distances. Compared to the 2001 EC readings, the EC in 2005 has increased slightly immediately below the slope of the EMS while the EC values further from the storage have not changed significantly. This reinforces the conclusion that the elevated values are a result of EMS seepage near the storage and ion exchange and mineral dissolution at greater distances.

2005 chloride, ammonium and potassium concentrations are elevated to depths of approximately one metre below the storage and 5 to 10 metres south of the inside side slope of Cell No. 1. Ion exchange of ammonium and potassium with magnesium and calcium and a general increase in solution ionic strength may have resulted in dissolution of minerals such as gypsum along with precipitation of calcium carbonate. This possible exchange and dissolution appears to have potentially produced elevated magnesium and sulphate concentrations to at least 3 metres below the storage and distances of up to 25 metres south of the inside slope of the storage. The 2005 ammonium and potassium levels have increased beneath the slope of the EMS to a depth of one metre compared to 2001 data. The 2001 data indicates that this EMS leachate seepage has caused the magnesium front to extend horizontally to the piezometres beneath the top of the berm and vertically 10 m downwards in 2005. High sulphate concentrations in 2001 and 2005 suggest that dissolution of minerals such as gypsum is continuing to occur due to high ionic strengths. Calcite precipitation appears to be occurring since the 2005 calcium concentrations have decreased compared to 2001.

In 2001, limited data was available at this cell. To date, Cell No. 2 at this site has experienced transport of ions to depths greater than three metres below the storage and distances up to 10 metres adjacent to the side of the storage. This is indicated by elevated concentrations of chloride, ammonium, potassium, sodium, magnesium, calcium and elevated electrical conductivity readings in the same locations. Ammonium, potassium, chloride, and EC concentrations have increased slightly in these locations compared to the 2001 concentrations that were available. The other ion concentrations appear to be unchanged between 2001 and 2005.

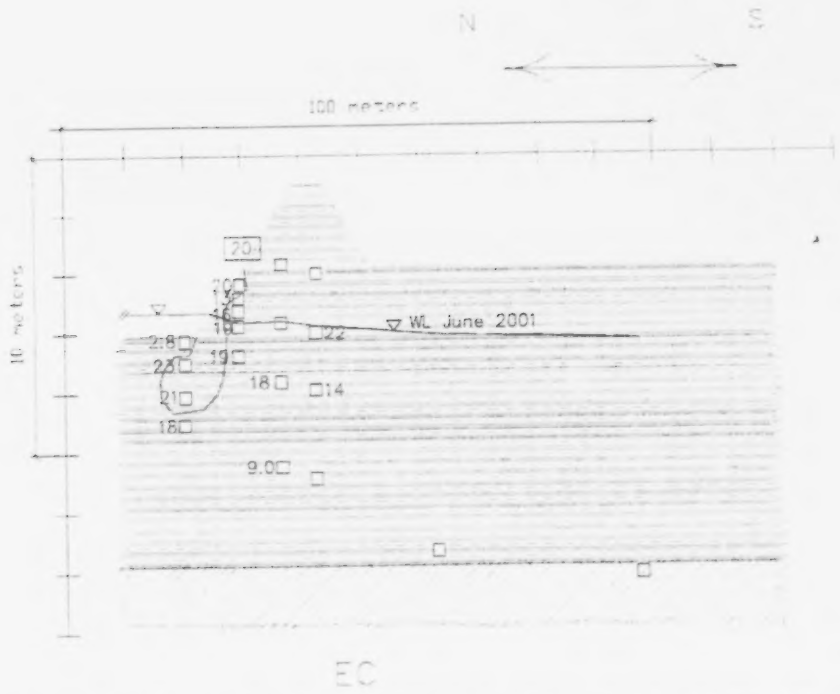

Figure 16. Site A, cell no. 1 electrical conductivity readings (mS/cm) from May 2001.

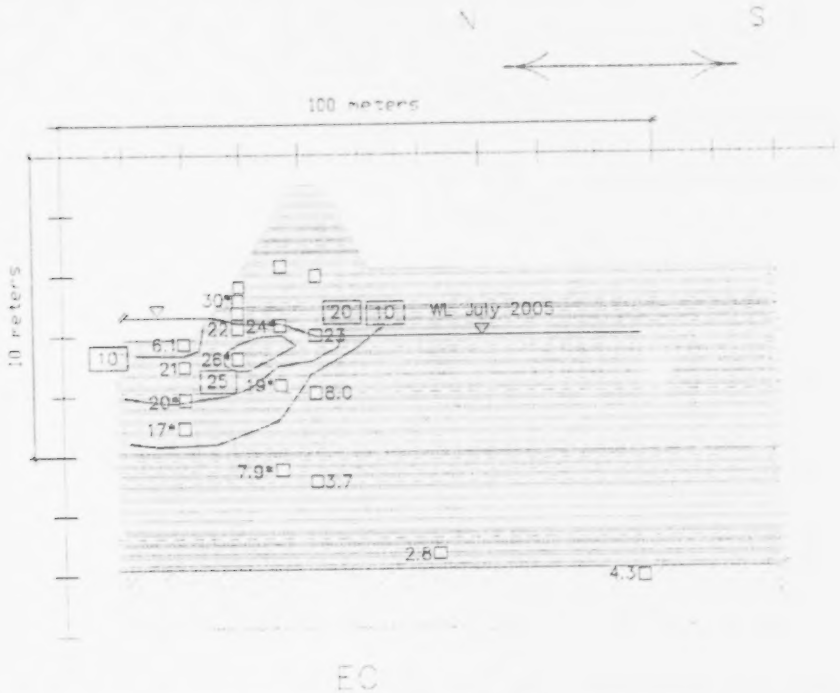

Figure 17. Site A, cell no. 1 electrical conductivity readings (mS/cm) from July 2005. * Indicates from a value from 2004, as 2005 data was unavailable.

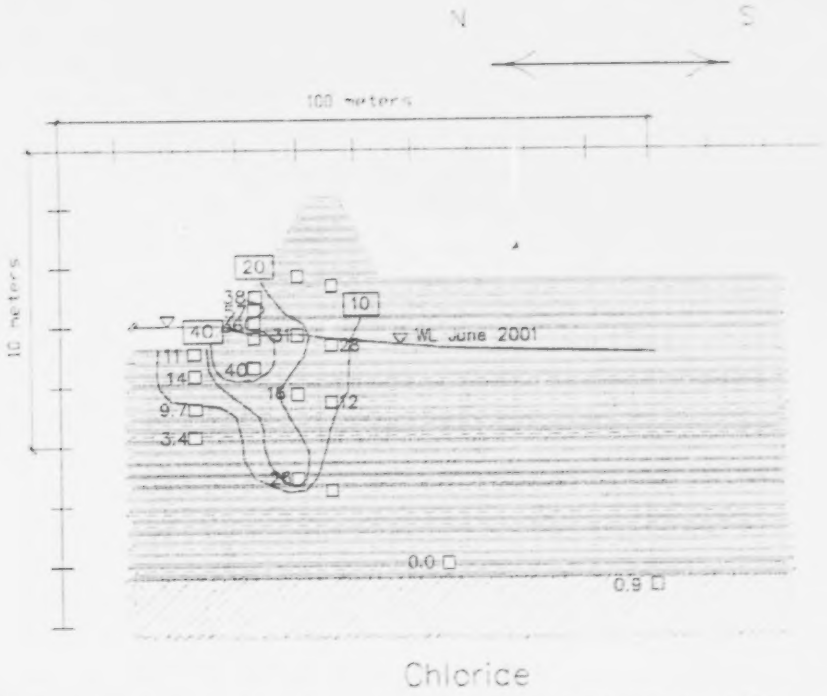

Figure 18. Site A. cell no. 1 chloride concentrations (meq/L) from May 2001.

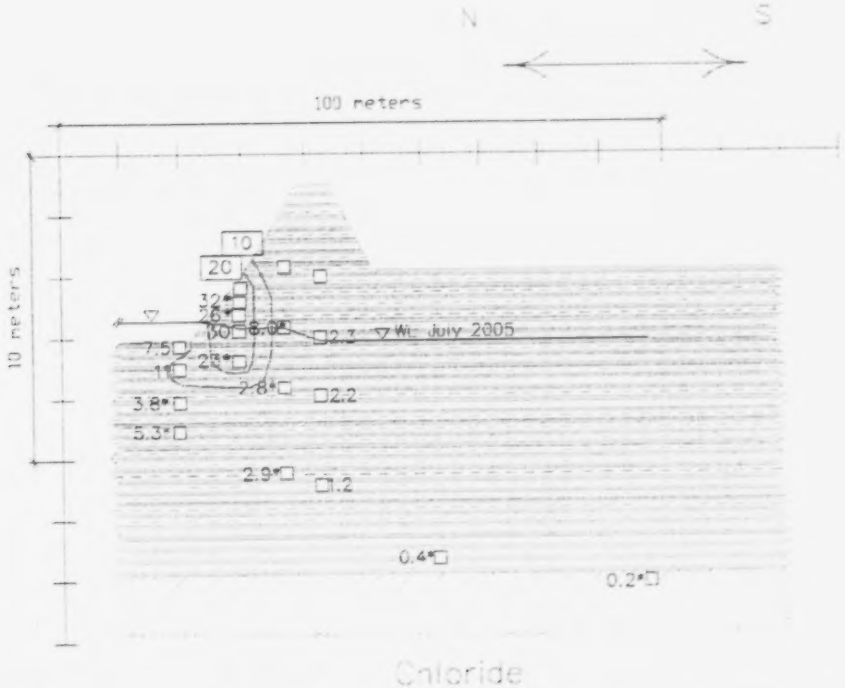

Figure 19. Site A. cell no. 1 chloride concentrations (meq/L) from July 2005. * Indicates from a value from 2004, as 2005 data was unavailable.

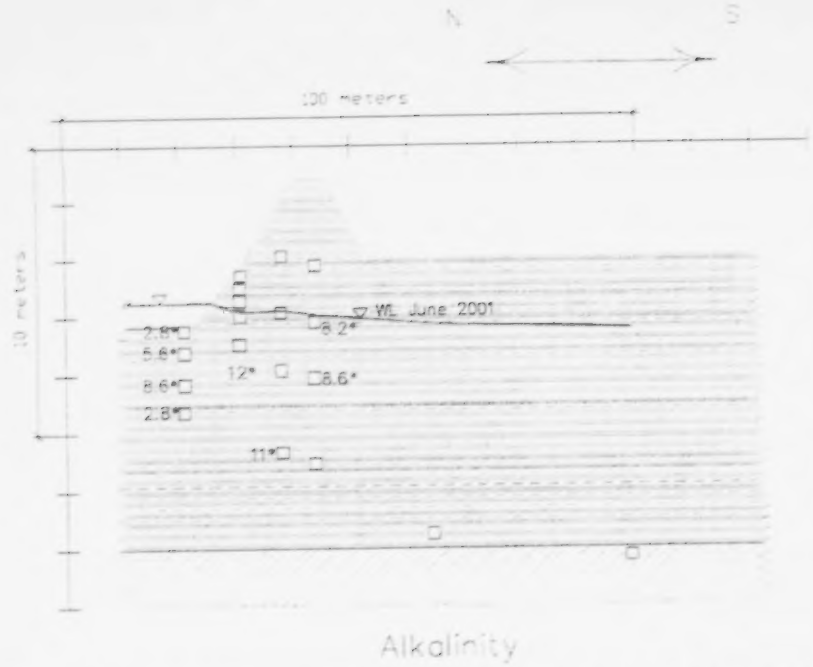

Figure 20. Site A, cell no. 1 alkalinity concentrations (meq/L $CaCO_3$) from May 2001.
*Indicates values from 2000, as 2001 data was not available.

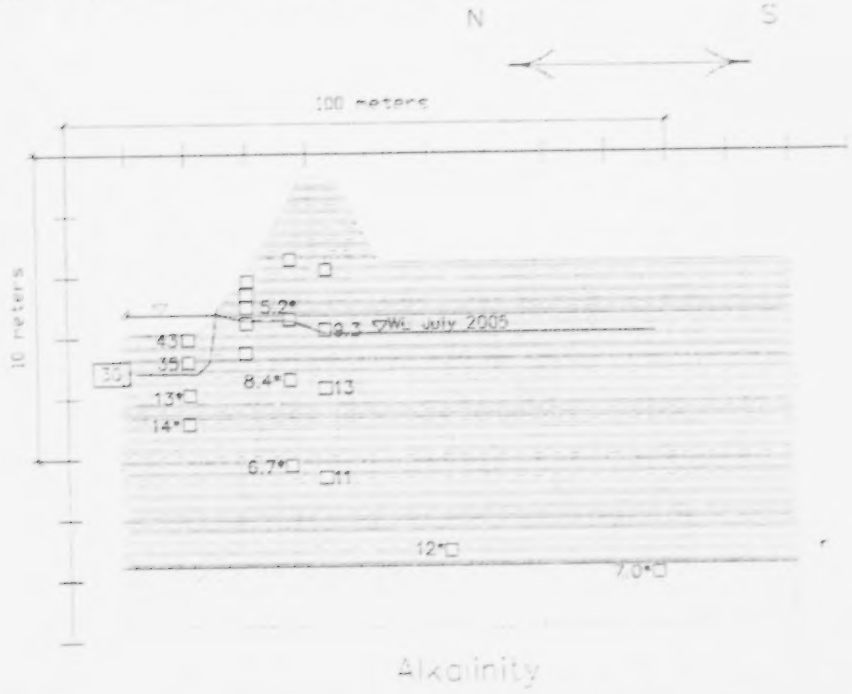

Figure 21. Site A, cell no. 1 alkalinity concentrations (meq/L $CaCO_3$) from July 2005.
*Indicates from a value from 2004, as 2005 data was unavailable.

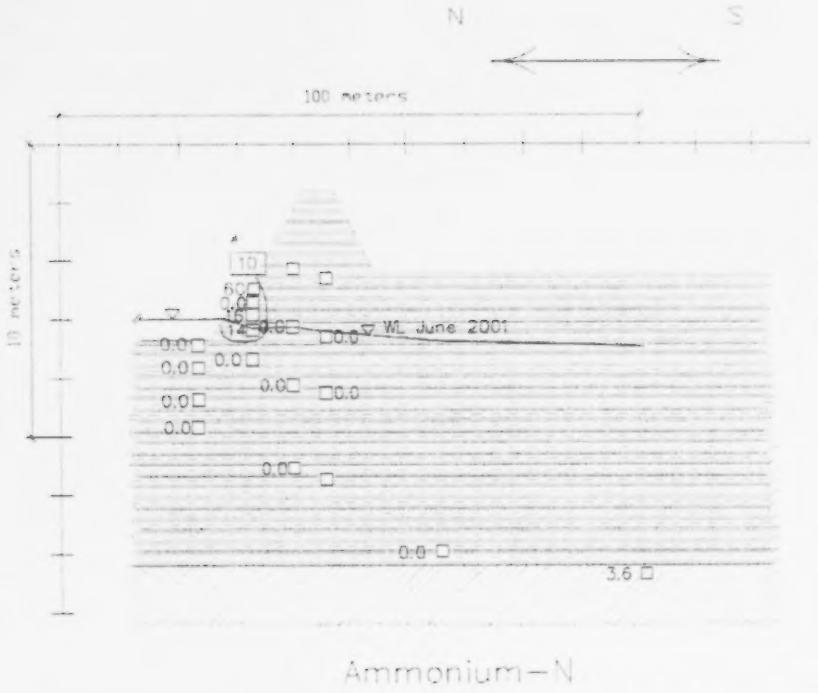

Figure 22. Site A, cell no. 1 ammonium concentrations (meq/L N) from May 2001.

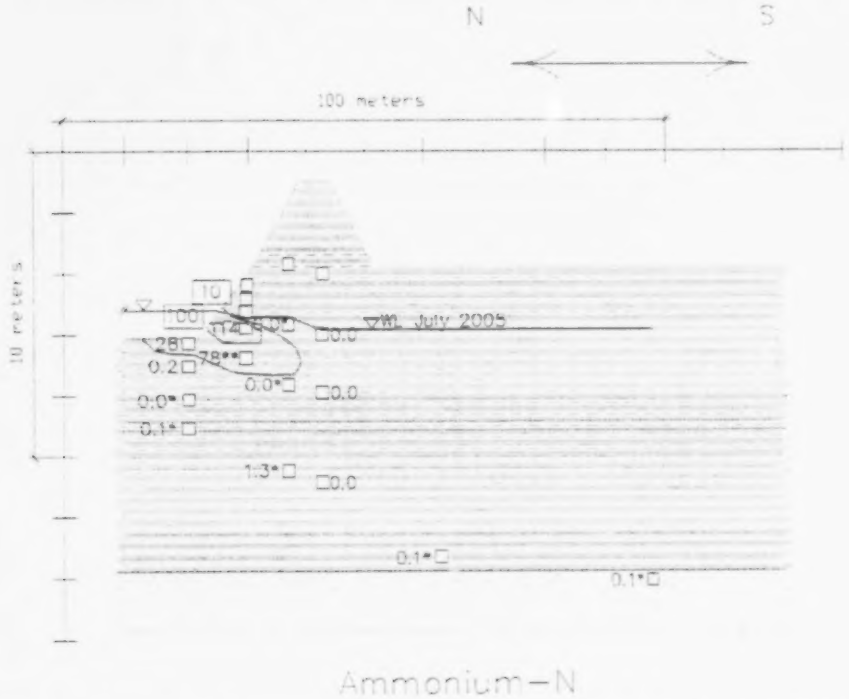

Figure 23. Site A, cell no. 1 ammonium concentrations (meq/L N) from July 2005.
*Indicates from a value from 2004, as 2005 data was unavailable.

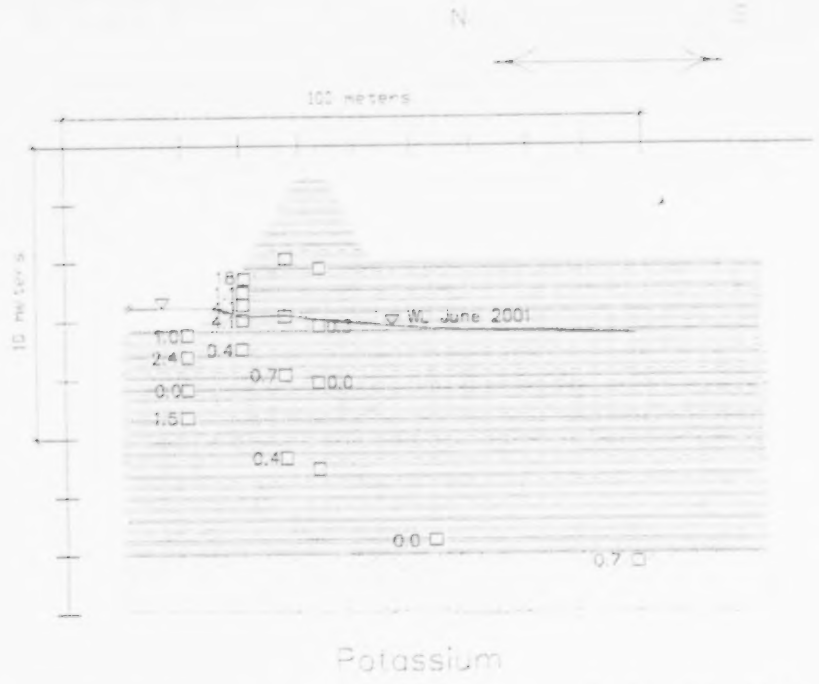

Figure 24. Site A. cell no. 1 potassium concentrations (meq/L) from May 2001.

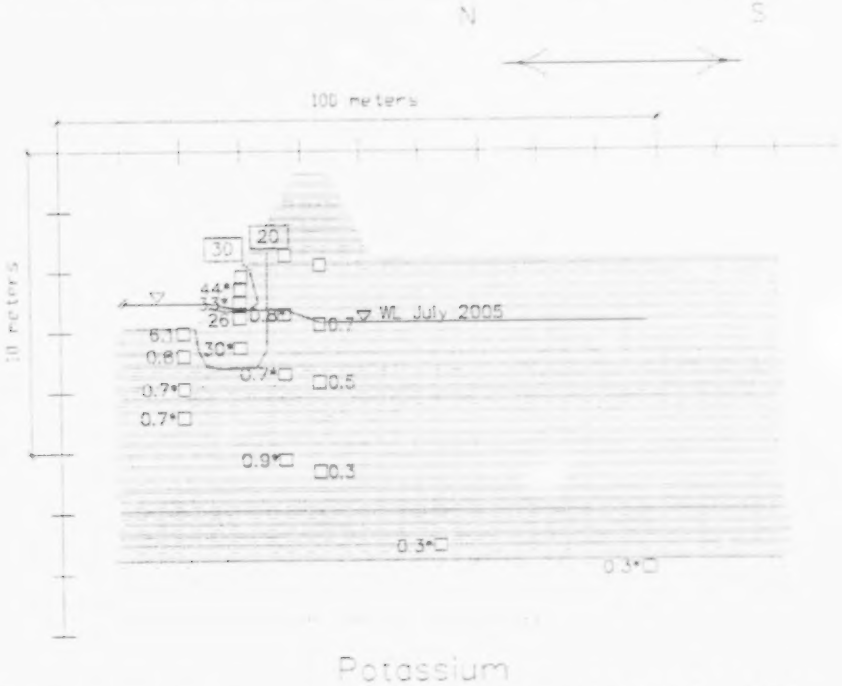

Figure 25. Site A. cell no. 1 potassium concentrations (meq/L) from July 2005.
*Indicates from a value from 2004. as 2005 data was unavailable.

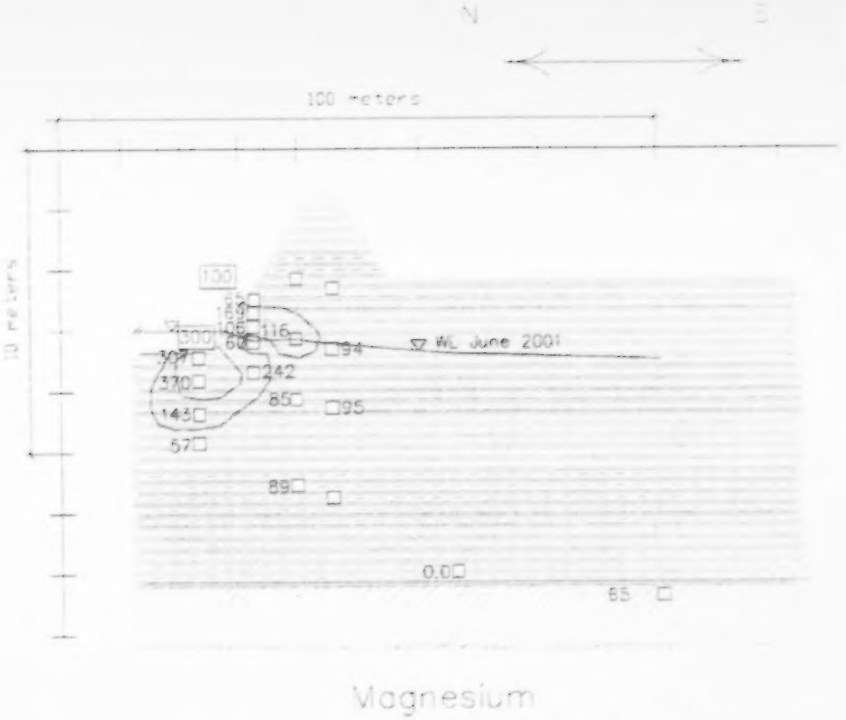

Figure 26. Site A, cell no. 1 magnesium concentrations (meq/L) from May 2001.

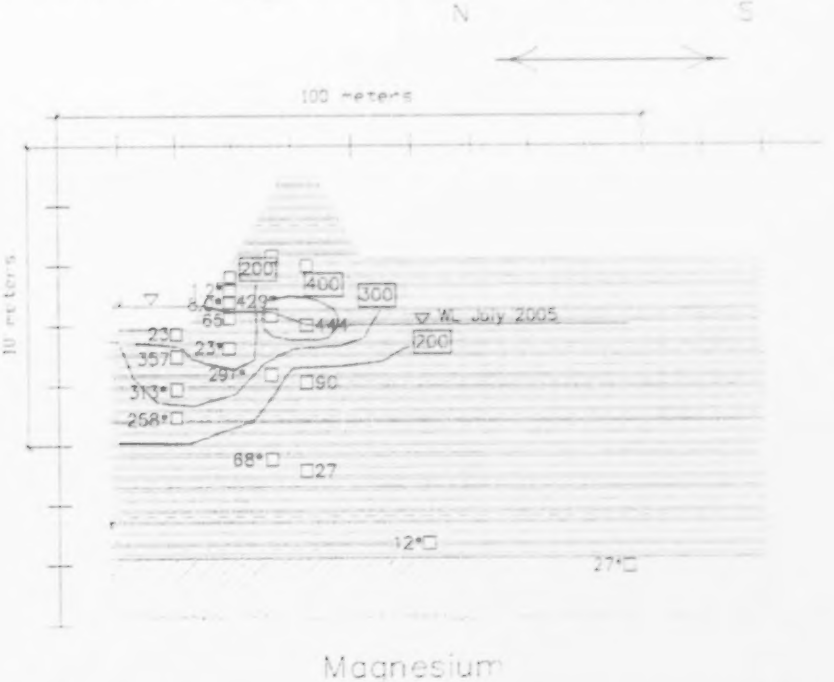

Figure 27. Site A, cell no. 1 magnesium concentrations (meq/L) from July 2005. * Indicates from a value from 2004, as 2005 data was unavailable.

Figure 28. Site A. cell no. 1 calcium concentrations (meq/L) from May 2001.

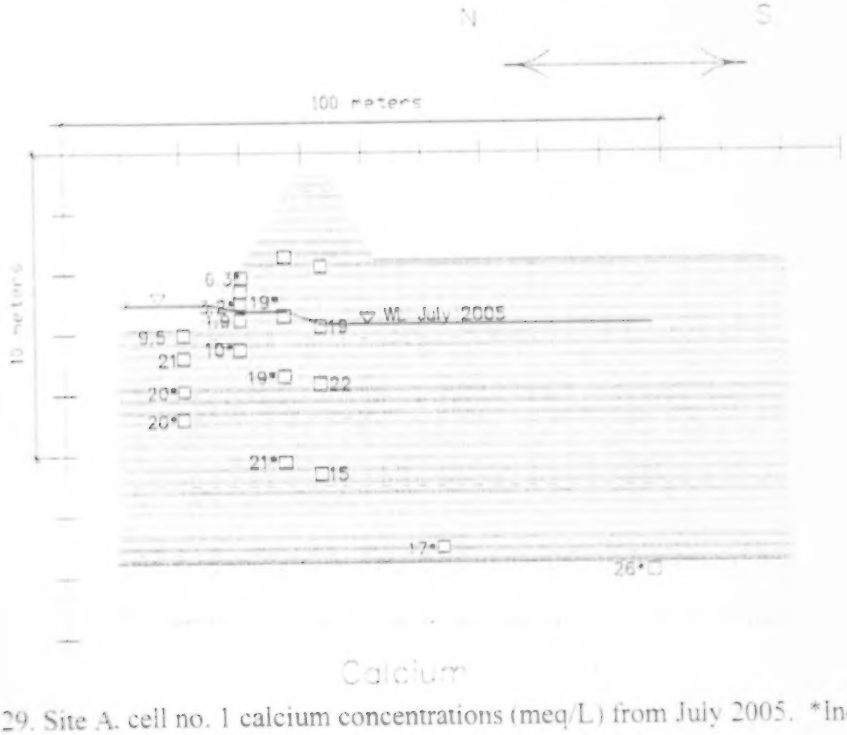

Figure 29. Site A. cell no. 1 calcium concentrations (meq/L) from July 2005. *Indicates from a value from 2004, as 2005 data was unavailable.

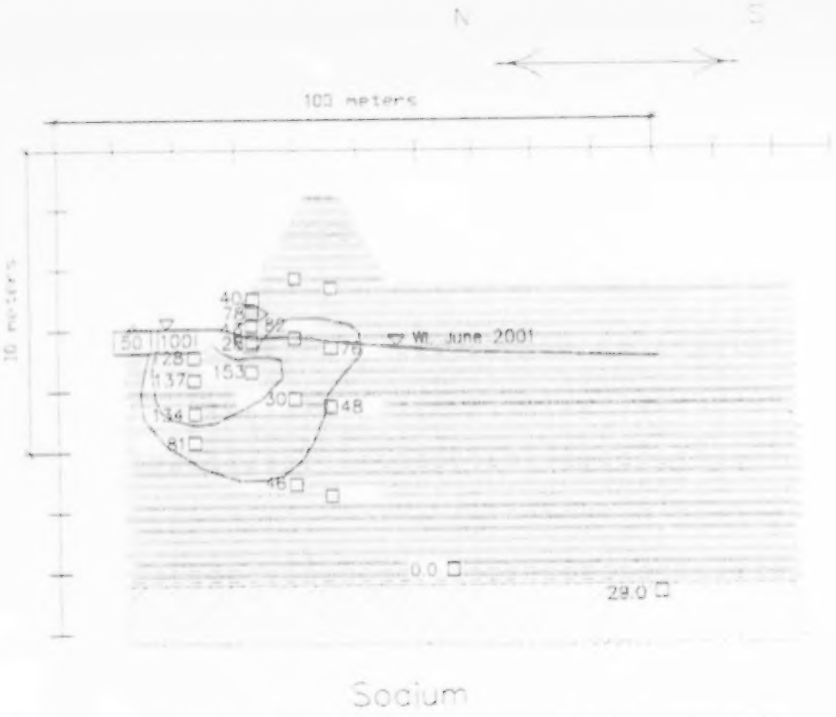

Figure 30. Site A, cell no. 1 sodium concentrations (meq/L) from May 2001.

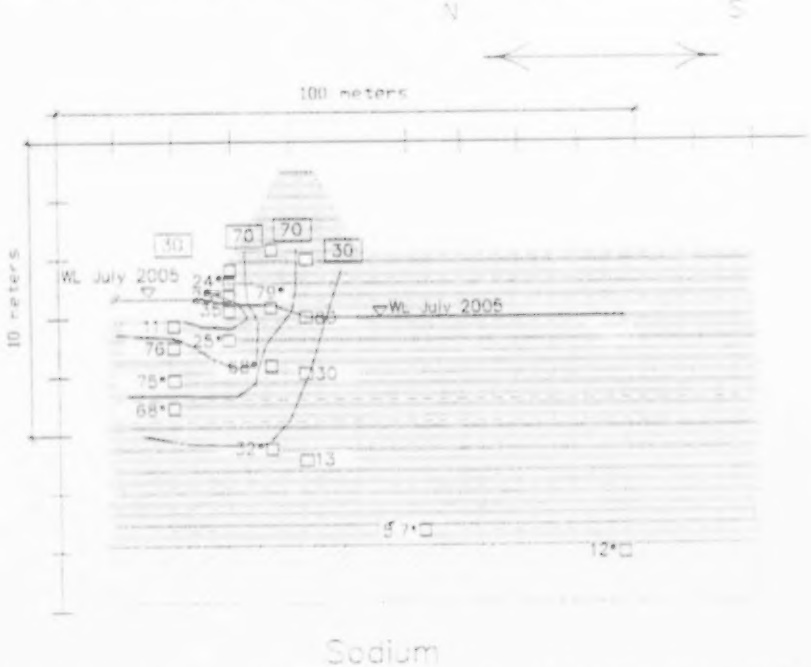

Figure 31. Site A, cell no. 1 sodium concentrations (meq/L) from July 2005. * Indicates from a value from 2004, as 2005 data was unavailable.

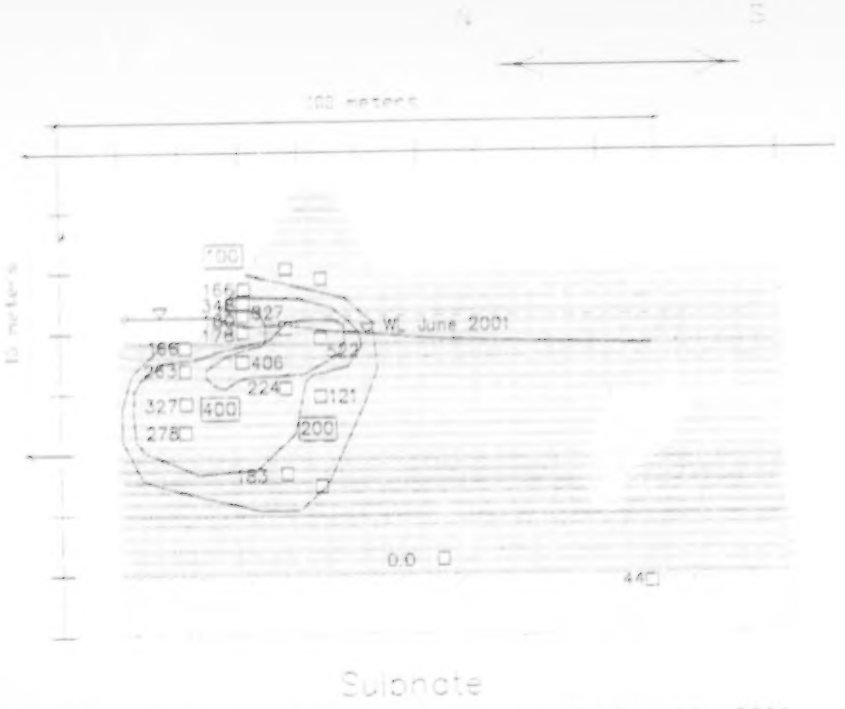

Figure 32. Site A, cell no. 1 sulphate concentrations (meq/L) from May 2001.

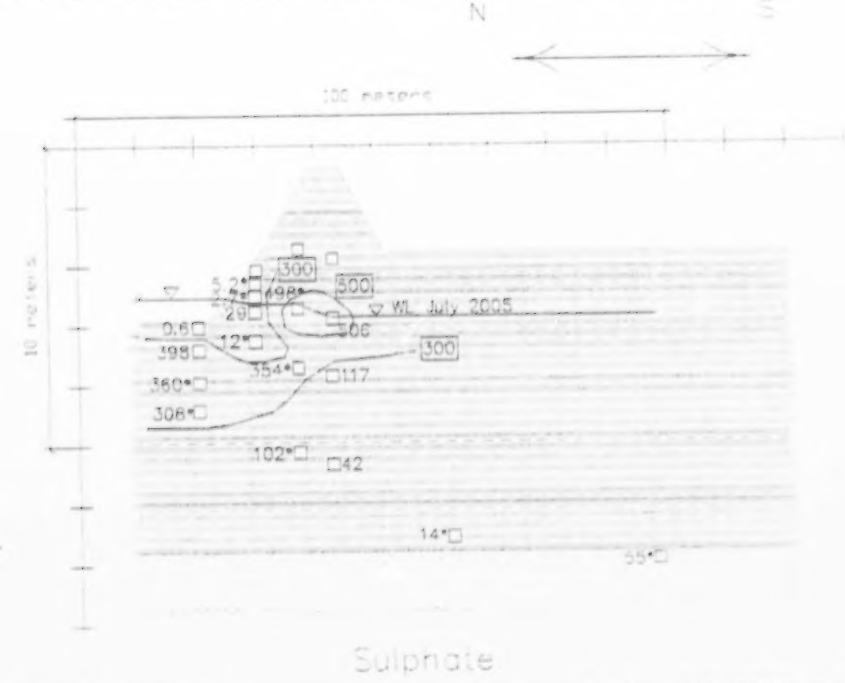

Figure 33. Site A, cell no. 1 sulphate concentrations (meq/L) from July 2005. * Indicates from a value from 2004, as 2005 data was unavailable.

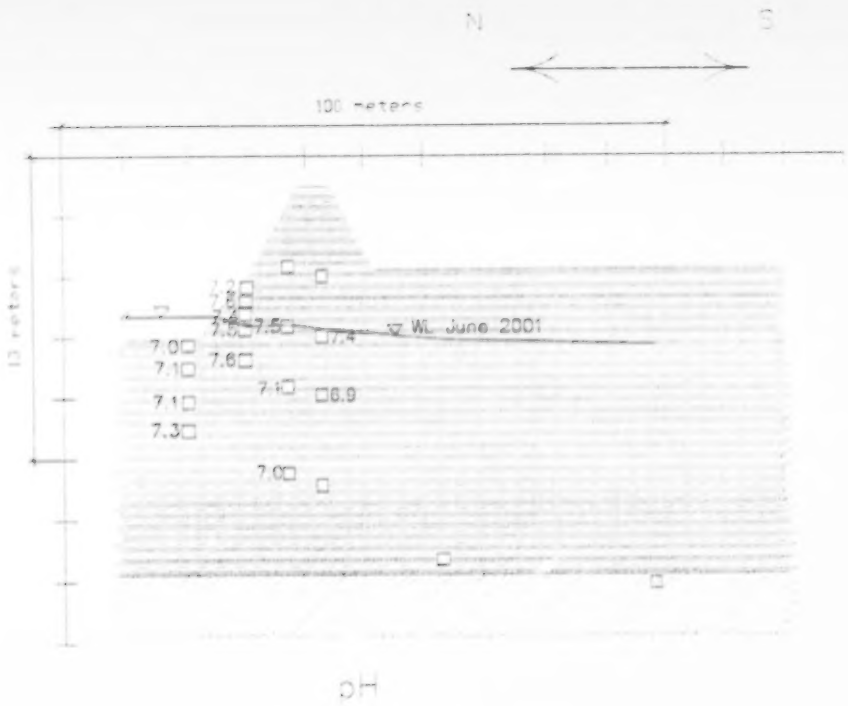

Figure 34. Site A. cell no. 1 pH readings from May 2001.

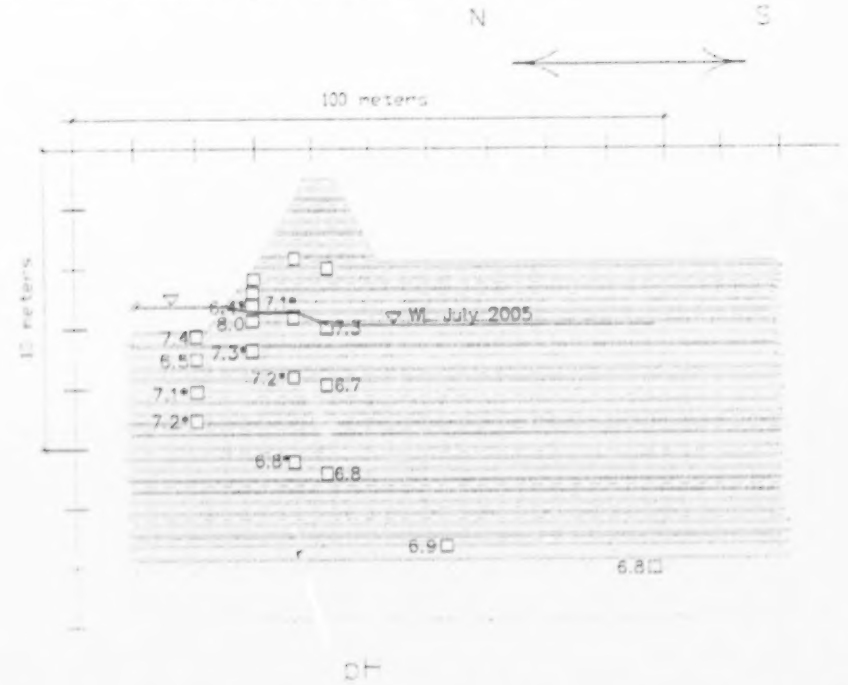

Figure 35. Site A. cell no. 1 pH readings from July 2005. * Indicates from a value from 2004, as 2005 data was unavailable.

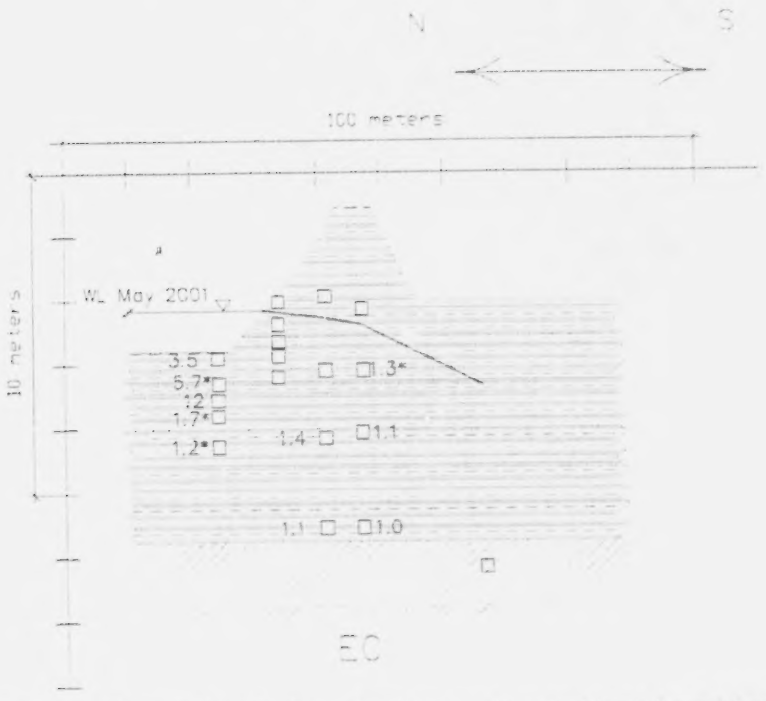

Figure 36. Site A, cell no. 2 electrical conductivity reading (mS/cm) from May 2001.
*Indicates values from 2000, as 2001 data was not available.

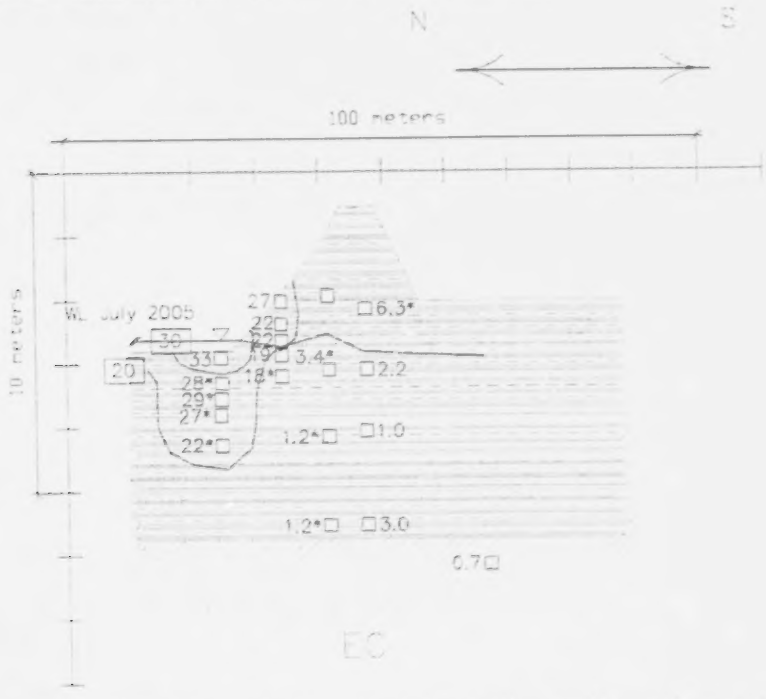

Figure 37. Site A, cell no. 2 electrical conductivity readings (mS/cm) from July 2005.
*Indicates a value from 2004, as 2005 data was unavailable.

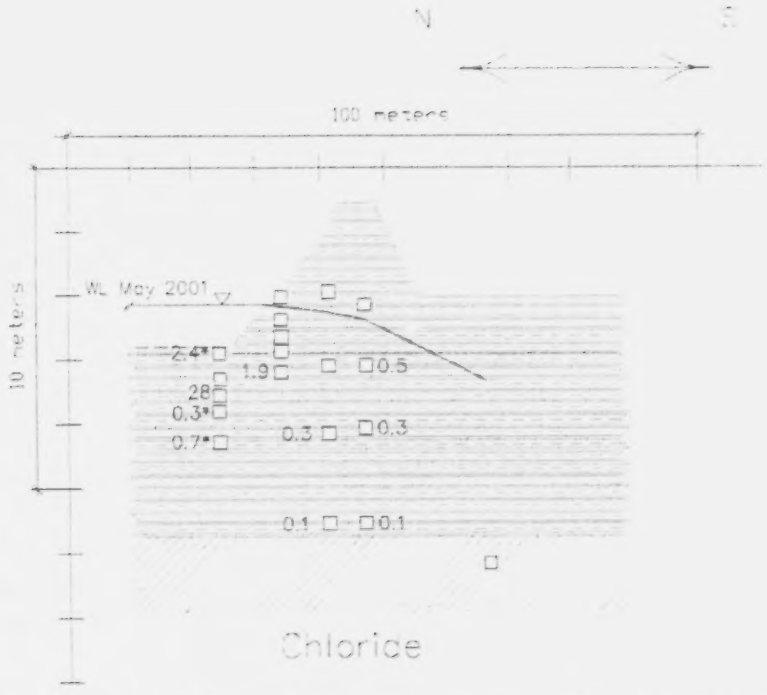

Figure 38. Site A, cell no. 2 chloride concentrations (meq/L) from May 2001. *Indicates values from 2000, as 2001 data was not available.

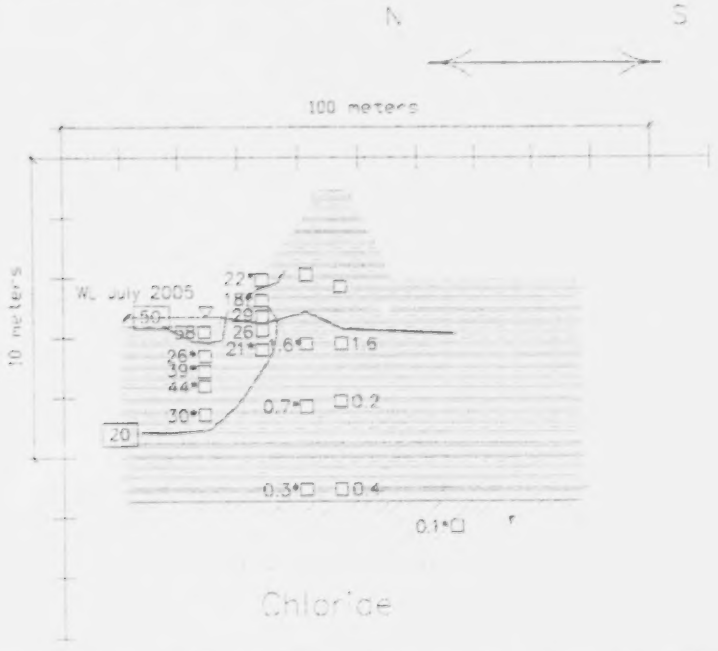

Figure 39. Site A, cell no. 2 chloride concentrations (meq/L) from July 2005. *Indicates from a value from 2004, as 2005 data was unavailable.

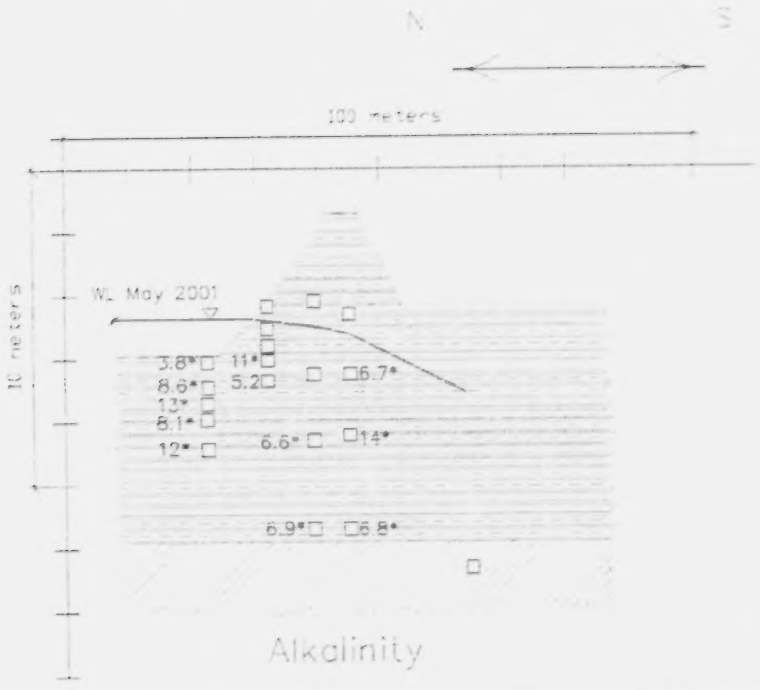

Figure 40. Site A, cell no. 2 alkalinity concentrations (meq/L $CaCO_3$) from May 2001.
*Indicates values from 2000, as 2001 data was not available.

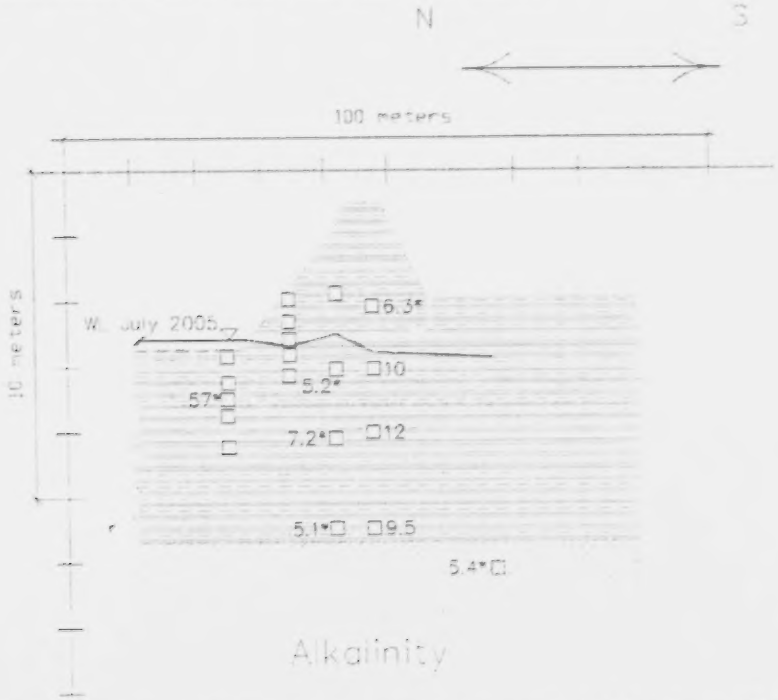

Figure 41. Site A, cell no. 2 alkalinity concentrations (meq/L $CaCO_3$) from July 2005.
*Indicates a value from 2004, as 2005 data was unavailable.

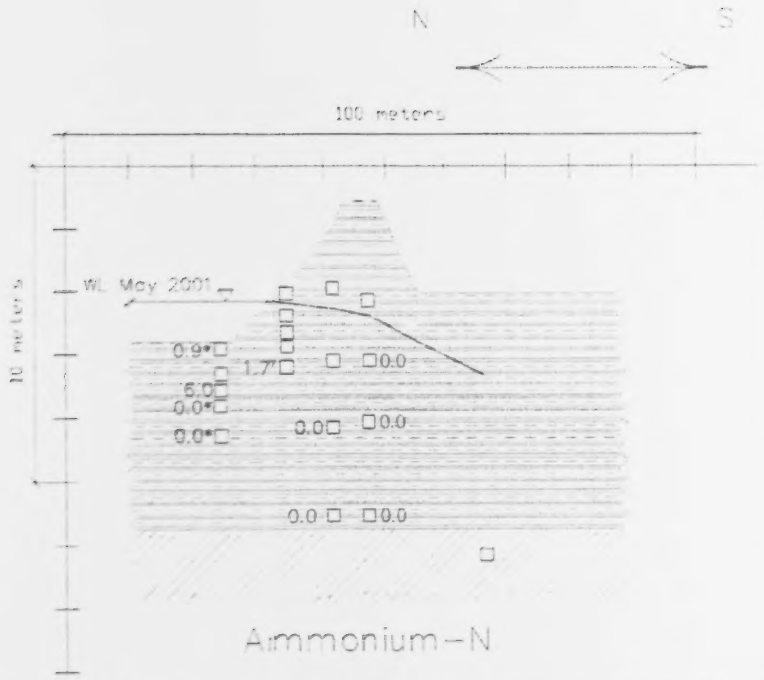

Figure 42. Site A, cell no. 2 ammonium concentrations (meq/L N) from May 2001. *Indicates values from 2000, as 2001 data was not available.

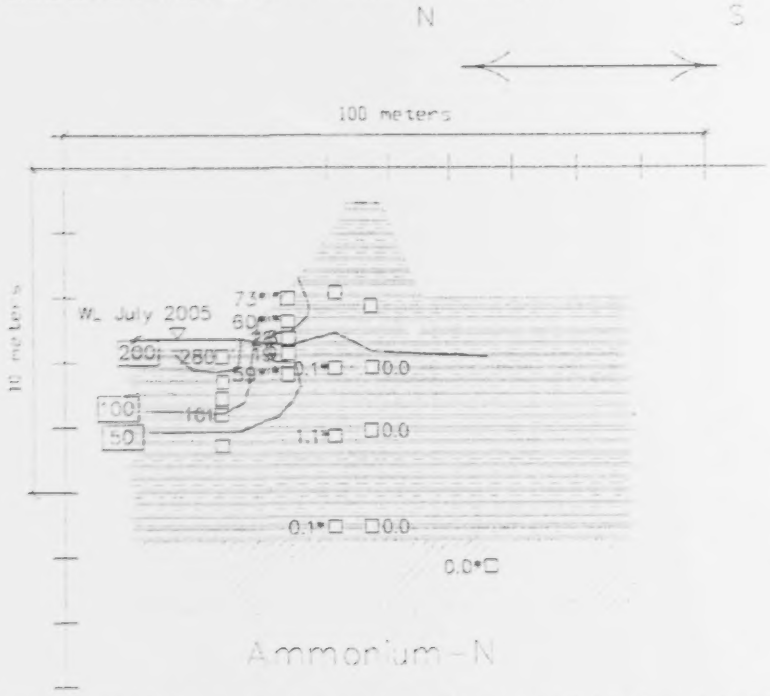

Figure 43. Site A, cell no. 2 ammonium concentrations (meq/L N) from July 2005. *Indicates a value from 2004, as 2005 data was unavailable. **Indicates a value from 2003, due to suspected laboratory error in 2004.

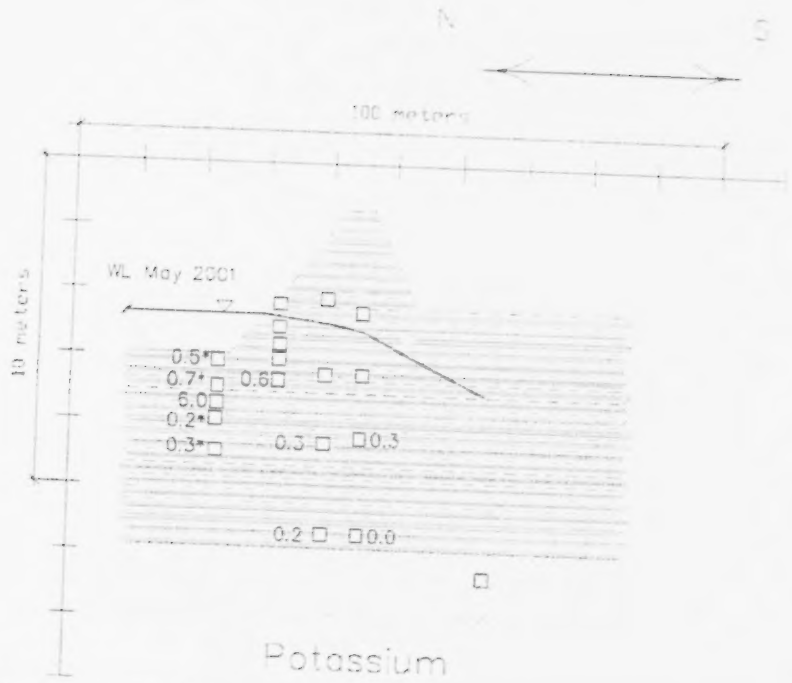

Figure 44. Site A. cell no. 2 potassium concentrations (meq/L) from May 2001. *Indicates values from 2000, as 2001 data was not available.

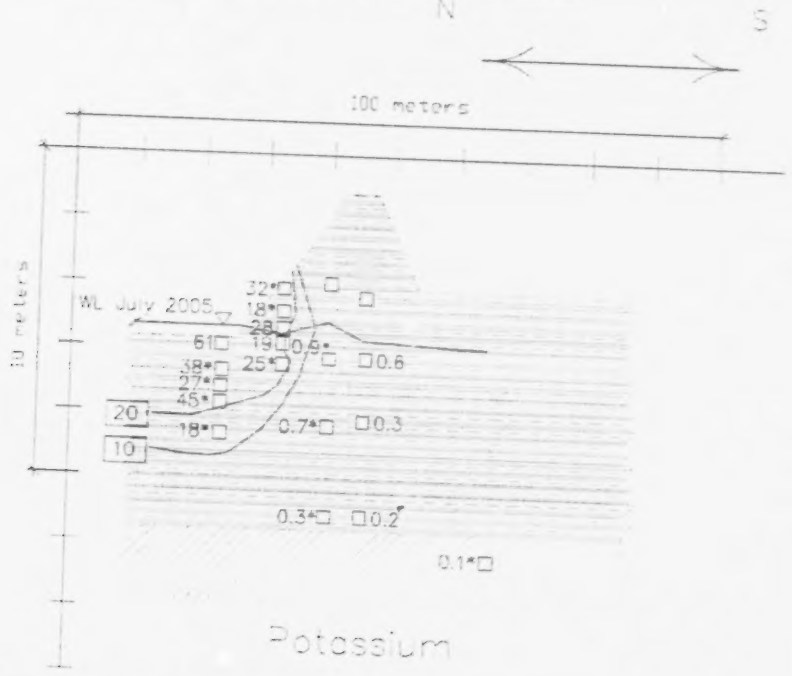

Figure 45. Site A. cell no. 2 potassium concentrations (meq/L) from July 2005. *Indicates a value from 2004, as 2005 data was unavailable.

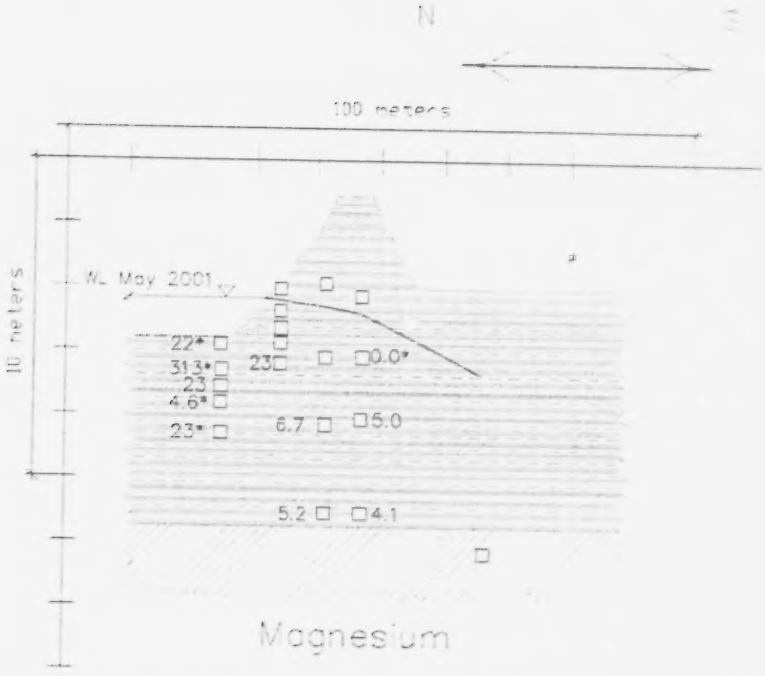

Figure 46. Site A. cell no. 2 magnesium concentrations (meq/L) from May 2001. *Indicates values from 2000, as 2001 data was not available.

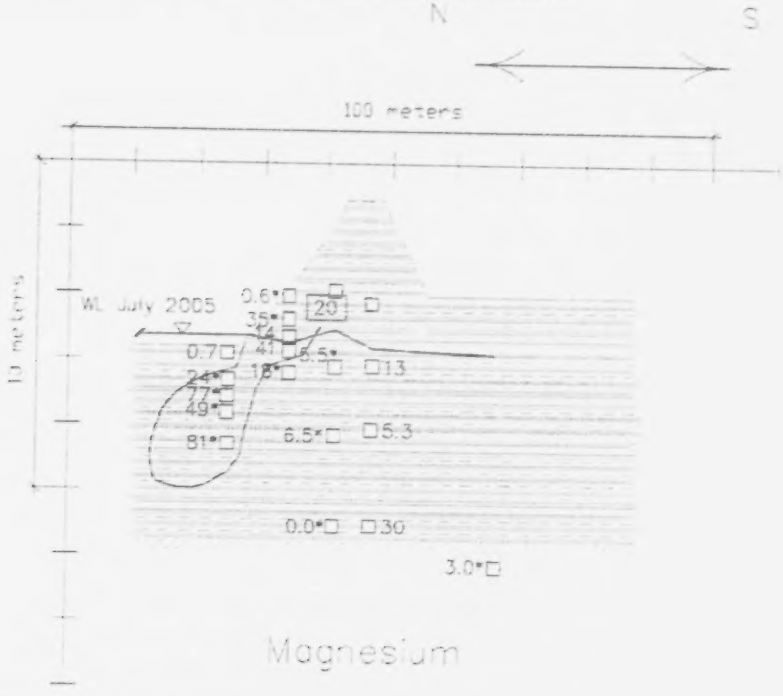

Figure 47. Site A. cell no. 2 magnesium concentrations (meq/L) from July 2005. *Indicates a value from 2004, as 2005 data was unavailable.

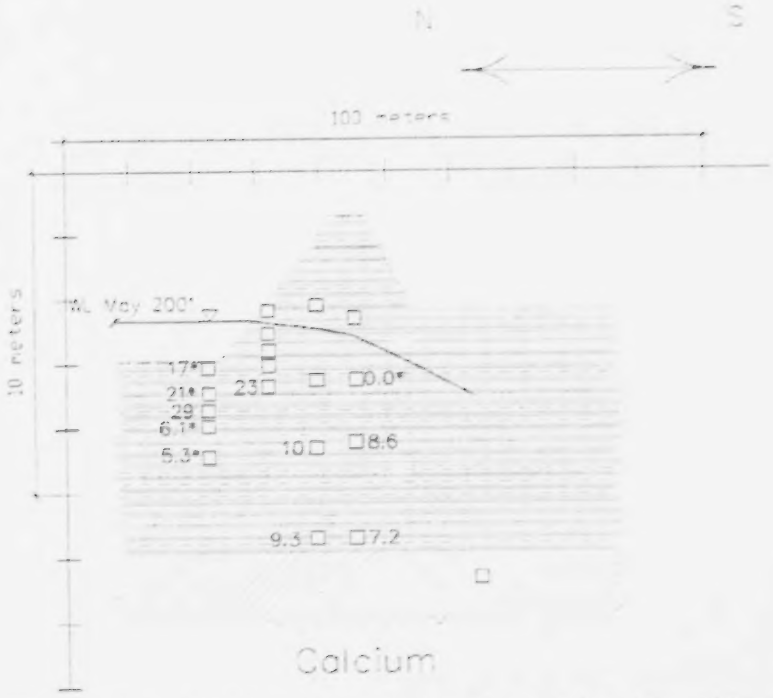

Figure 48. Site A. cell no. 2 calcium concentrations (meq/L) from May 2001. *Indicates values from 2000. as 2001 data was not available.

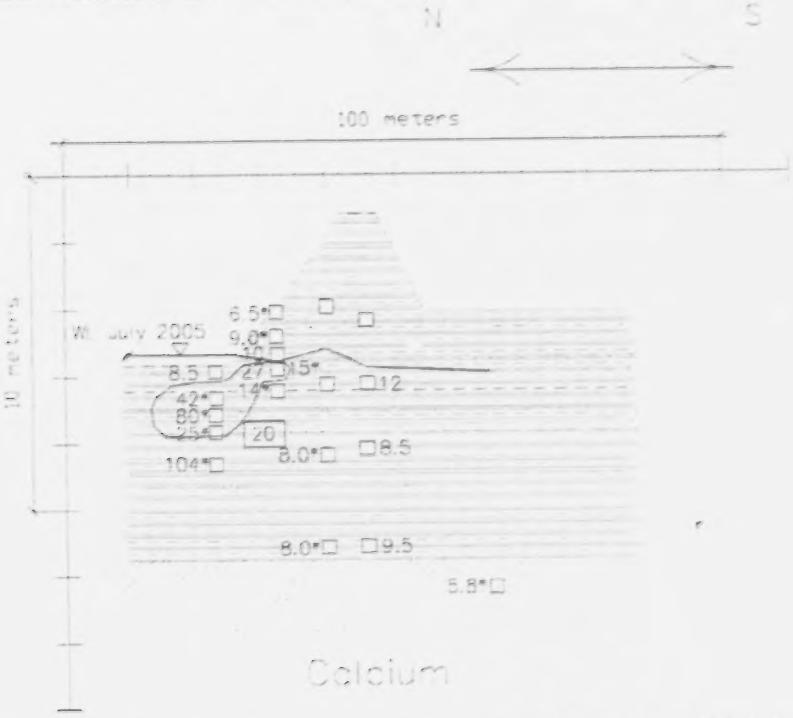

Figure 49. Site A. cell no. 2 calcium concentrations (meq/L) from July 2005. *Indicates a value from 2004. as 2005 data was unavailable.

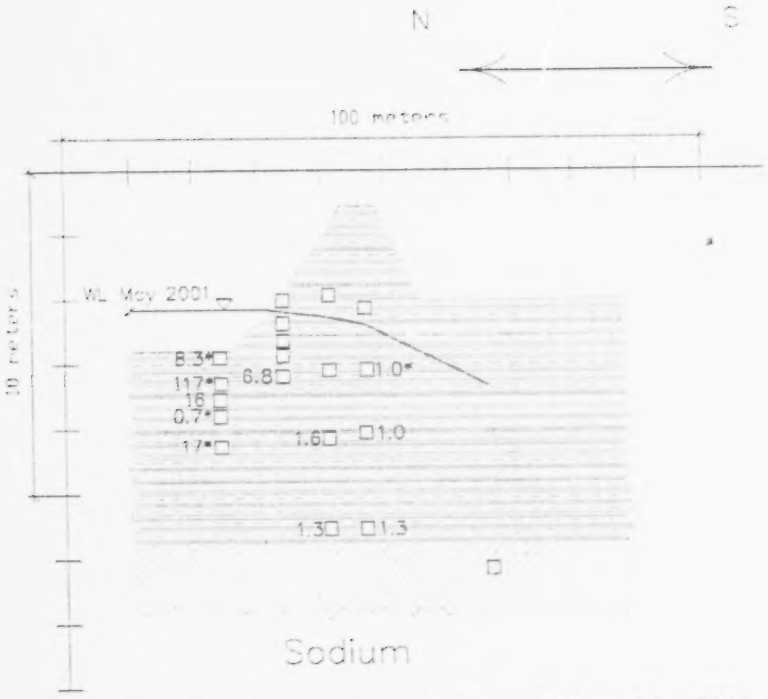

Figure 50. Site A. cell no. 2 sodium concentrations (meq/L) from May 2001. *Indicates values from 2000. as 2001 data was not available.

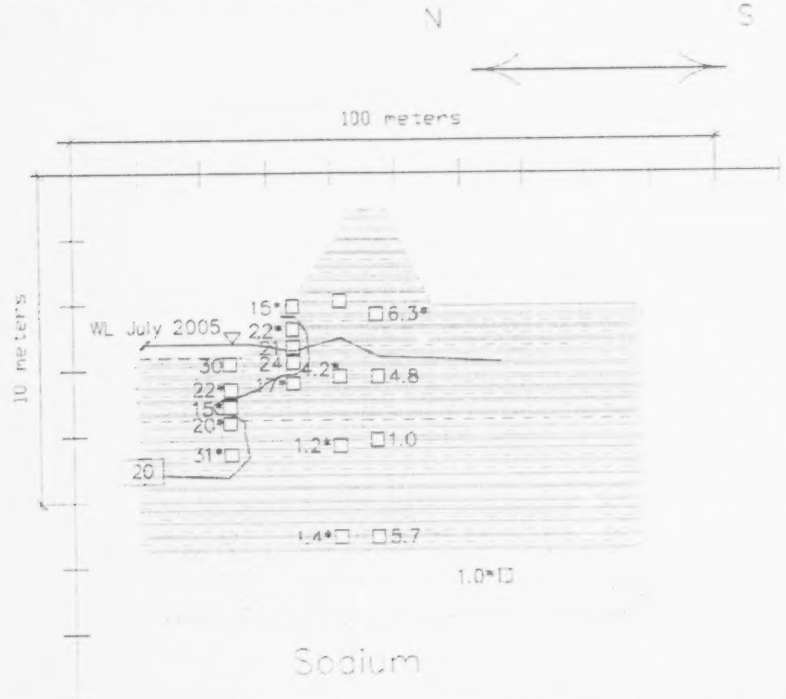

Figure 51. Site A. cell no. 2 sodium concentrations (meq/L) from July 2005. *Indicates a value from 2004. as 2005 data was unavailable.

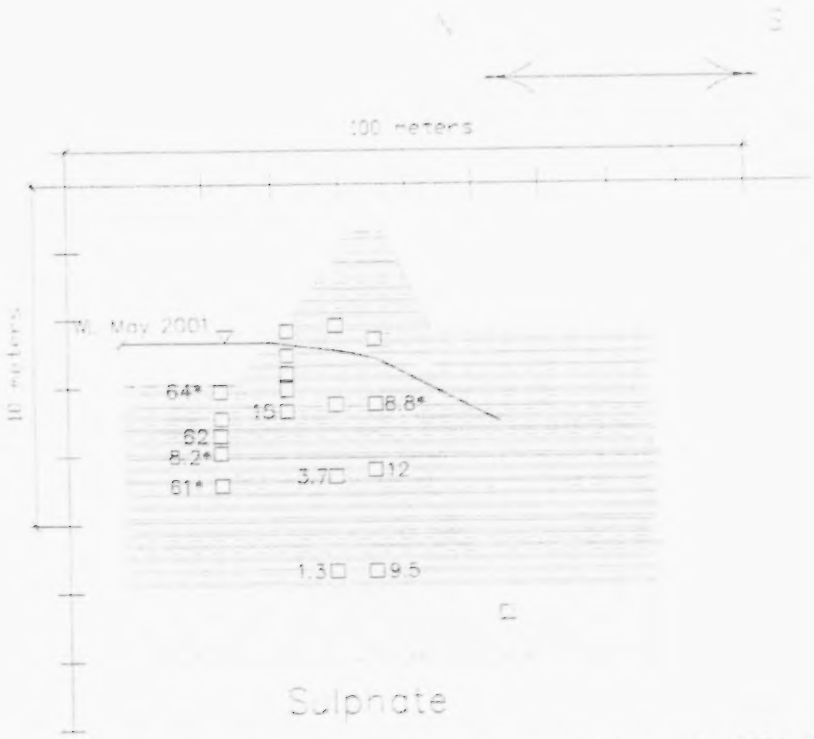

Figure 52. Site A, cell no. 2 sulphate concentrations (meq/L) from May 2001. *Indicates values from 2000, as 2001 data was not available.

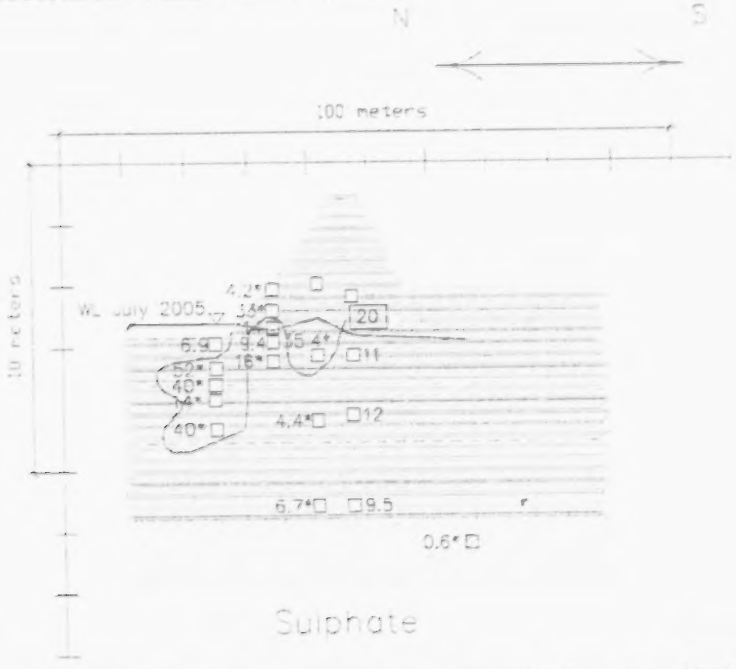

Figure 53. Site A, cell no. 2 sulphate concentrations (meq/L) from July 2005. *Indicates a value from 2004, as 2005 data was unavailable.

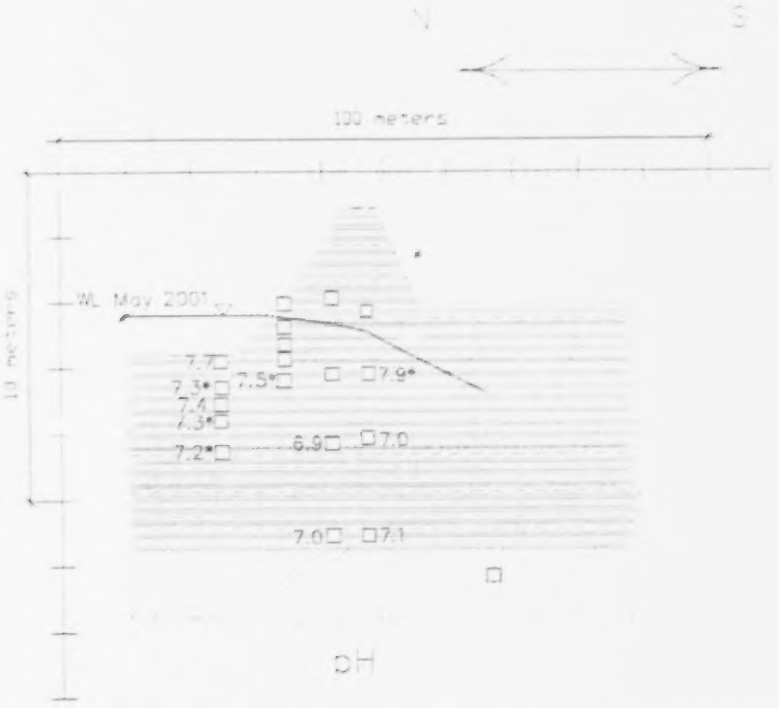

Figure 54. Site A. cell no. 2 pH readings from May 2001. *Indicates values from 2000, as 2001 data was not available.

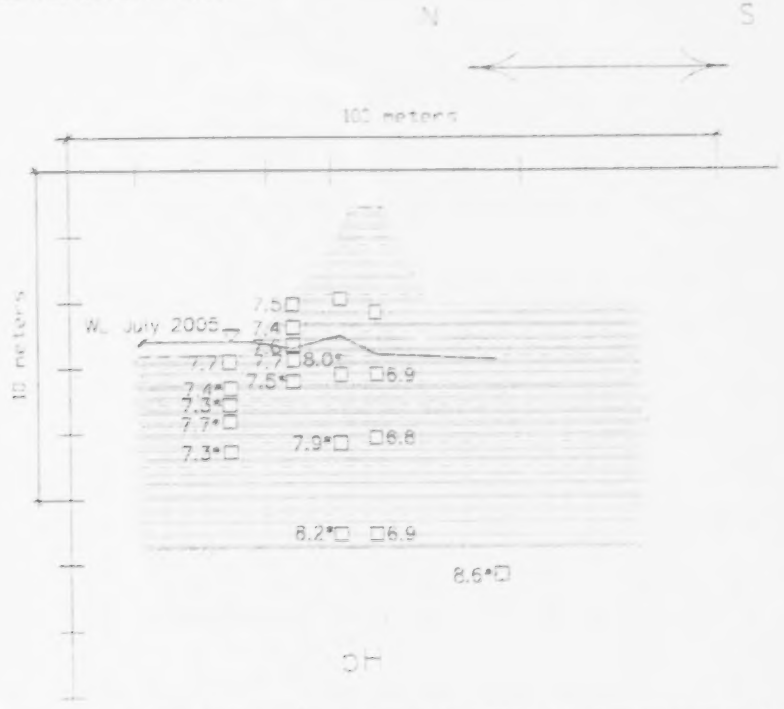

Figure 55. Site A. cell no. 2 pH readings from July 2005. *Indicates a value from 2004, as 2005 data was unavailable.

Site B

Groundwater mounding at this site has occurred at a rate equal to the rate of filling of the EMS. It is speculated that this is due to the near saturated conditions in the surrounding soils allowing immediate response when a very small amount of fluid is added to the system. It is important to note that groundwater mounding does not indicate leakage but does reveal the hydraulic gradients affecting potential seepage.

Figures 41 to 80 show geologic cross sections of the site with concentration profiles for electrical conductivity, chloride, alkalinity, ammonium, potassium, magnesium, calcium, sodium, sulphate and pH in May 2001 and July 2005.

In 2005, ion concentrations greater than 10 meq/L below and adjacent to Cell No. 1 (Primary or Solids Cell) occur to a depth of approximately three metres below the storage and extend approximately 3 to 6 metres parallel west of the side slope. This is indicated by chloride, alkalinity, ammonium, potassium and sodium as well as by sulphate reduction in the same area and is confirmed by electrical conductivities at the same locations. The only noteworthy changes from 2001 to 2005 were the increase of ammonium, potassium, and chloride concentrations immediately below the cell bottom and slope.

Ion concentrations below Cell No. 2 (secondary or liquid Cell) in 2005 are not as clearly defined. Chloride and alkalinity concentrations appear to extend to depths of 1.5 to 3 metres below the EMS respectively and extend 6 to 8 metres west of the inside toe of the side slope. These concentrations have only increased from 2001 immediately below the bottom of the cell and the slope of the cell.

Ammonium and potassium transport patterns are similar to the area of impact indicated by elevated electrical conductivities and by the area experiencing sulphate reduction. The area of elevated chloride concentrations appear to correlate with areas of elevated sodium concentrations and the area of elevated alkalinity appears to correlate with areas of high calcium concentrations. This may indicate that chloride and alkalinity are being affected by sodium chloride and calcite concentrations within the parent material or ammonium and potassium are significantly attenuated compared to these anions. Calcium concentrations have increased in 2005, compared to 2001, in areas where ammonium and potassium concentrations indicate seepage (beneath storage and slope of storage).

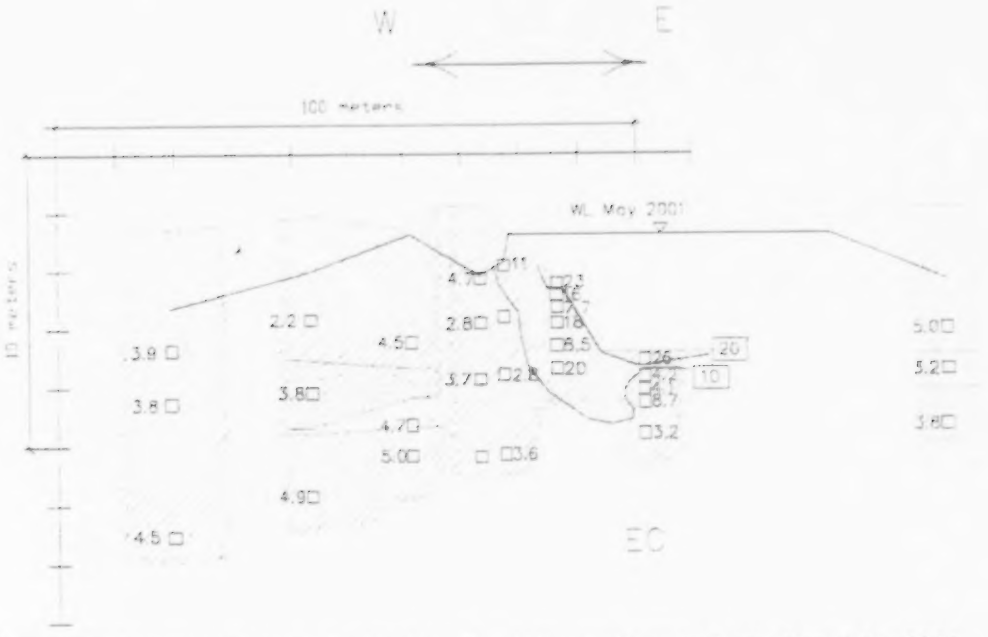

Figure 56. Site B, cell no. 1 electrical conductivity readings (mS/cm) from May 2001.

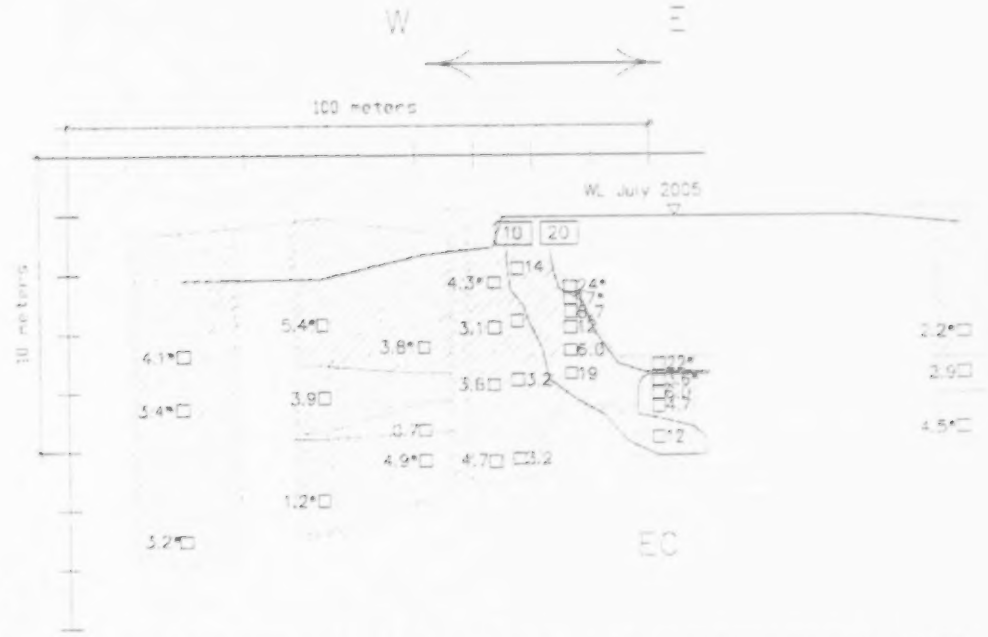

Figure 57. Site B, cell no. 1 electrical conductivity readings (mS/cm) from July 2005.
*Indicates a value from 2004, as 2005 data was not available.

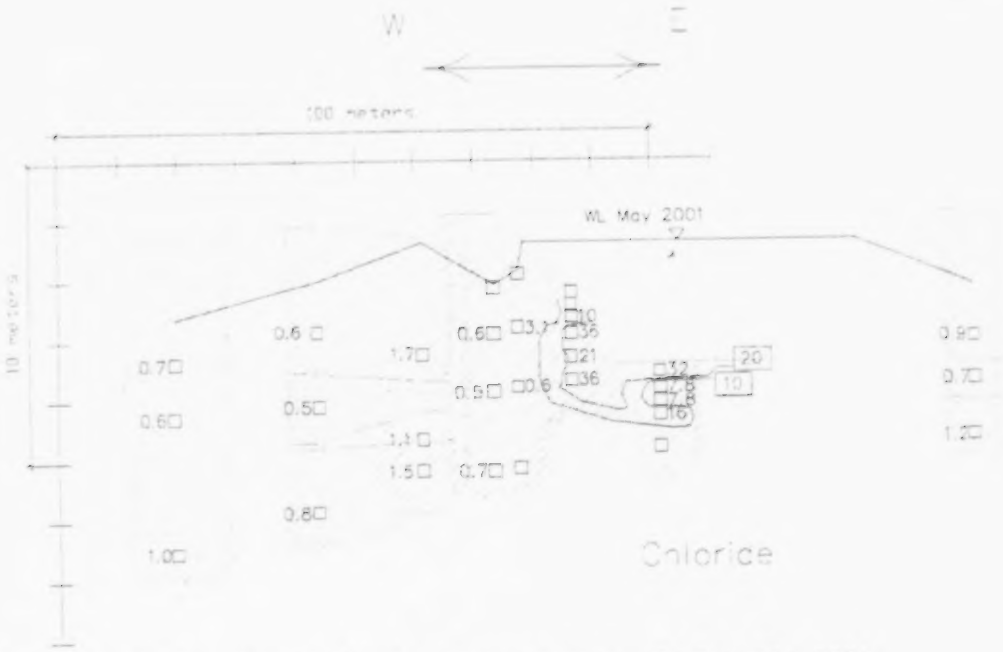

Figure 58. Site B. cell no. 1 chloride concentrations (meq/L) from May 2001.

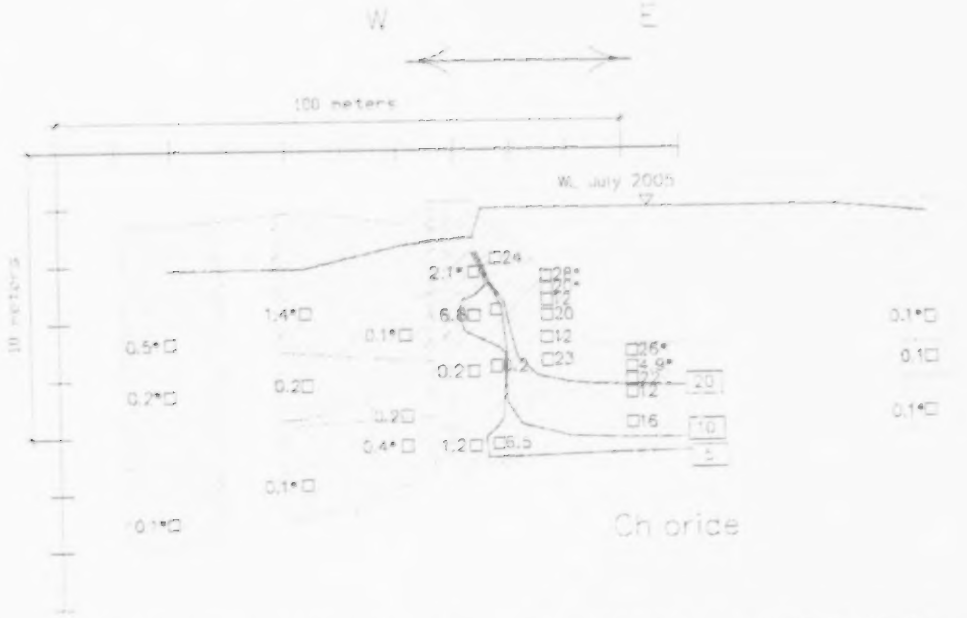

Figure 59. Site B. cell no. 1 chloride concentrations (meq/L) from July 2005. *Indicates a value from 2004, as 2005 data was not available.

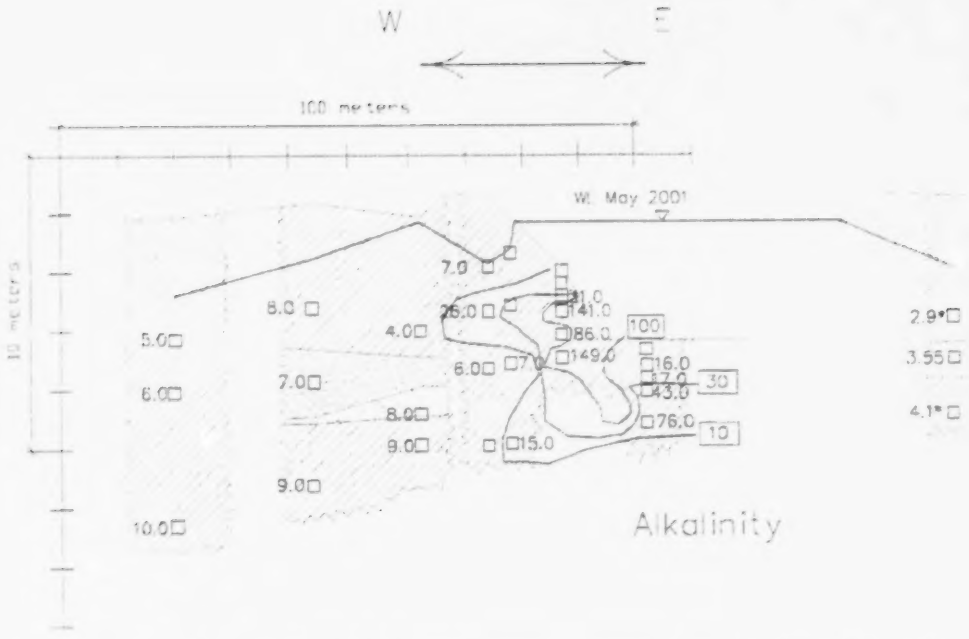

Figure 60. Site B. cell no. 1 alkalinity concentrations (meq/L $CaCO_3$)from May 2001.

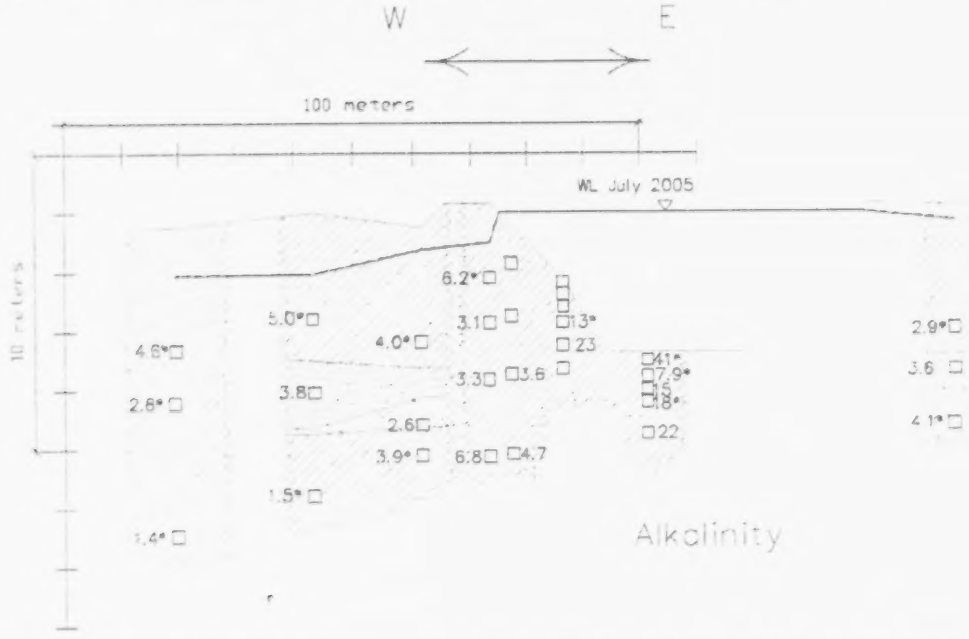

Figure 61. Site B. cell no. 1 alkalinity concentrations (meq/L $CaCO_3$) from July 2005. *Indicates a value from 2004, as 2005 data was not available.

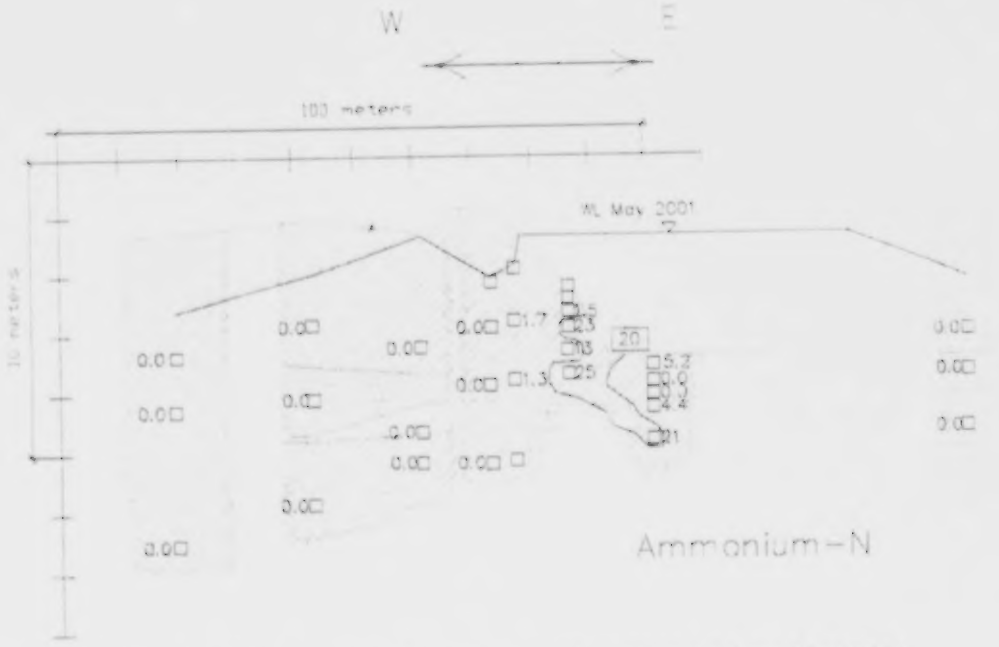

Figure 62. Site B, cell no. 1 ammonium concentrations (meq/L) from May 2001.

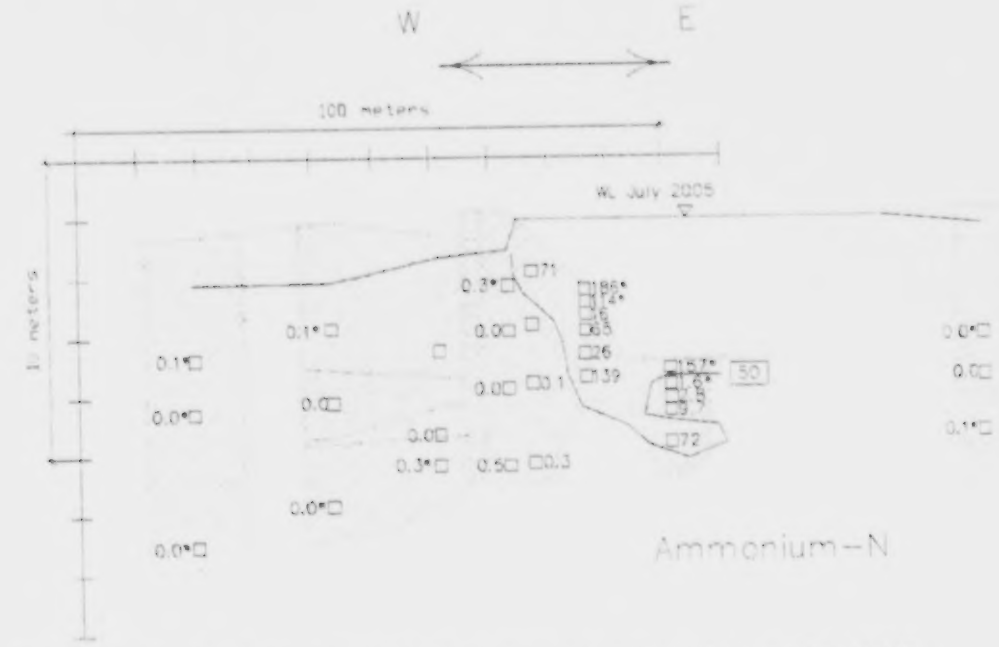

Figure 63. Site B, cell no. 1 ammonium concentrations (meq/L) from July 2005.
*Indicates a value from 2004, as 2005 data was not available.

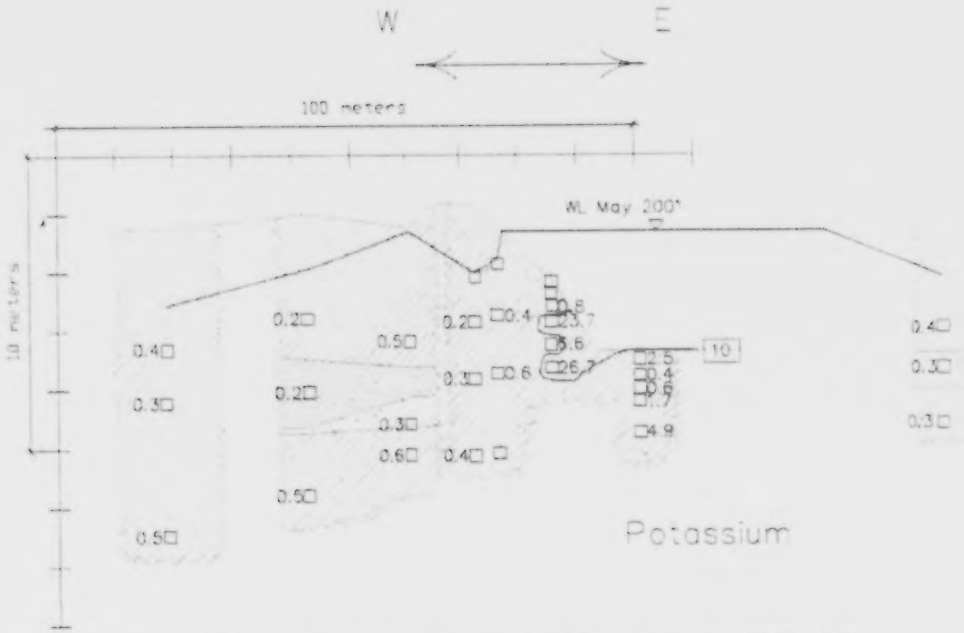

Figure 64. Site B, cell no. 1 potassium concentrations (meq/L) from May 2001.

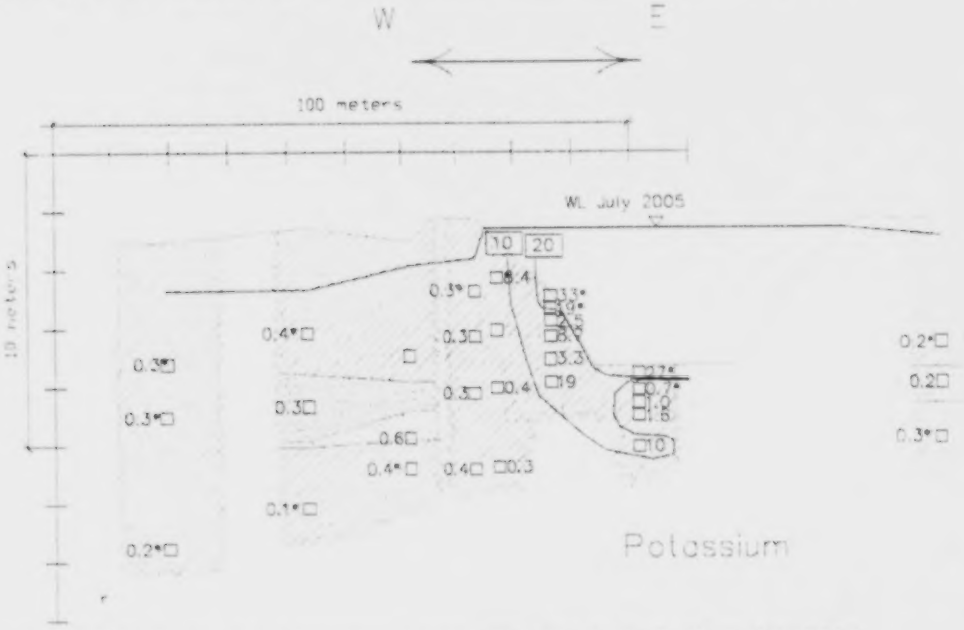

Figure 65. Site B, cell no. 1 potassium concentrations (meq/L) from July 2005.
*Indicates a value from 2004, as 2005 data was not available.

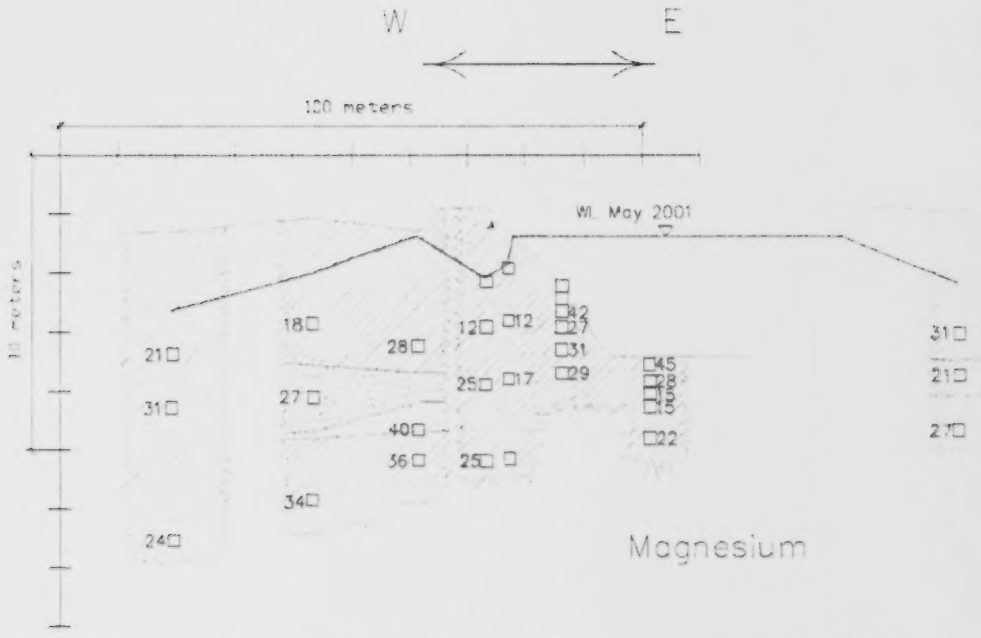

Figure 66. Site B, cell no. 1 magnesium concentrations (meq/L) from May 2001.

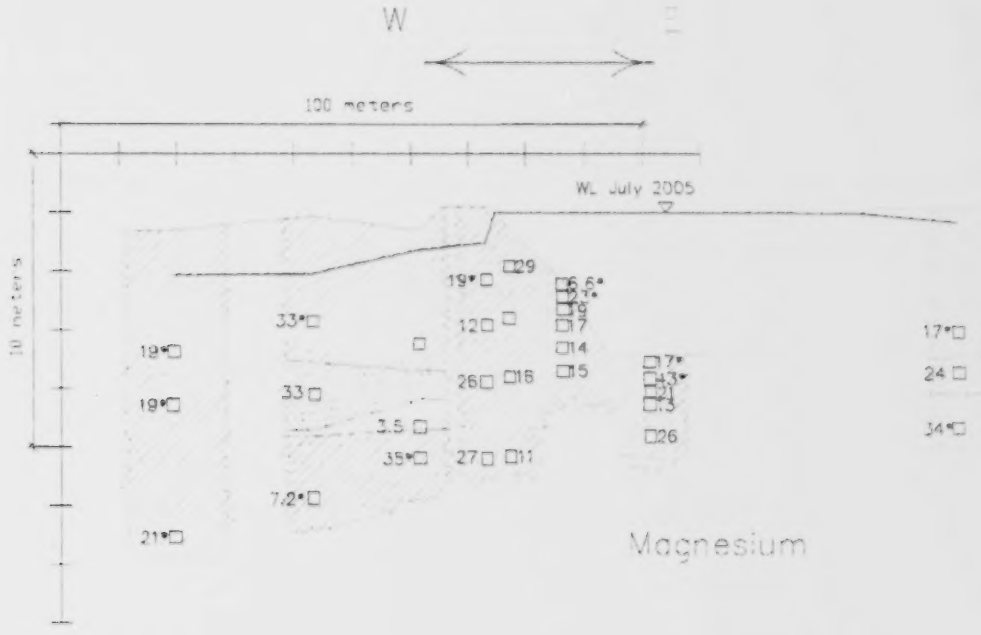

Figure 67. Site B, cell no. 1 magnesium concentrations (meq/L) from July 2005.
*Indicates a value from 2004, as 2005 data was not available.

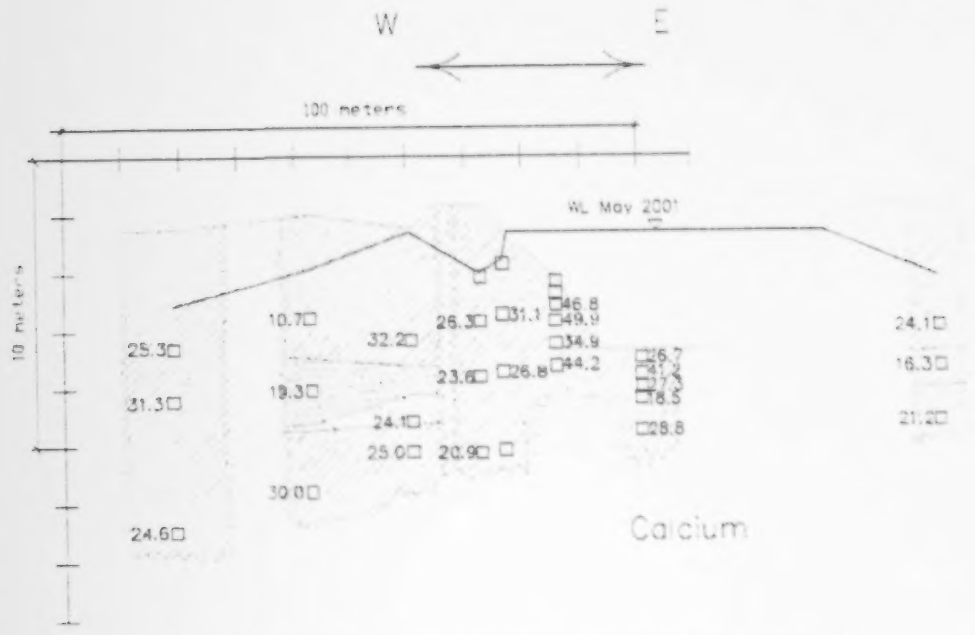

Figure 68. Site B, cell no. 1 calcium concentrations (meq/L) from May 2001.

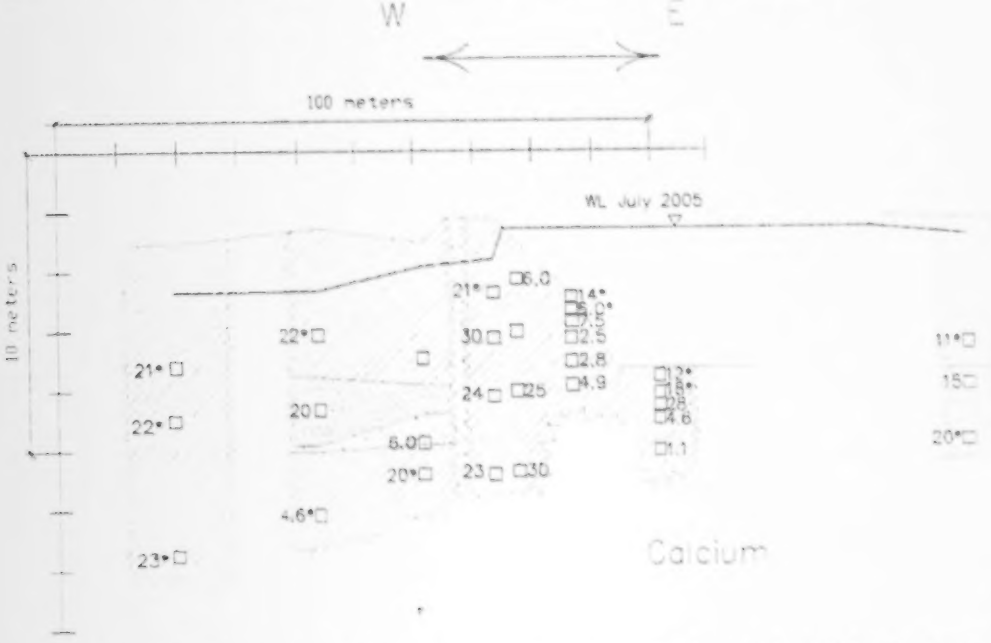

Figure 69. Site B, cell no. 1 calcium concentrations (meq/L) from July 2005. *Indicates a value from 2004, as 2005 data was not available.

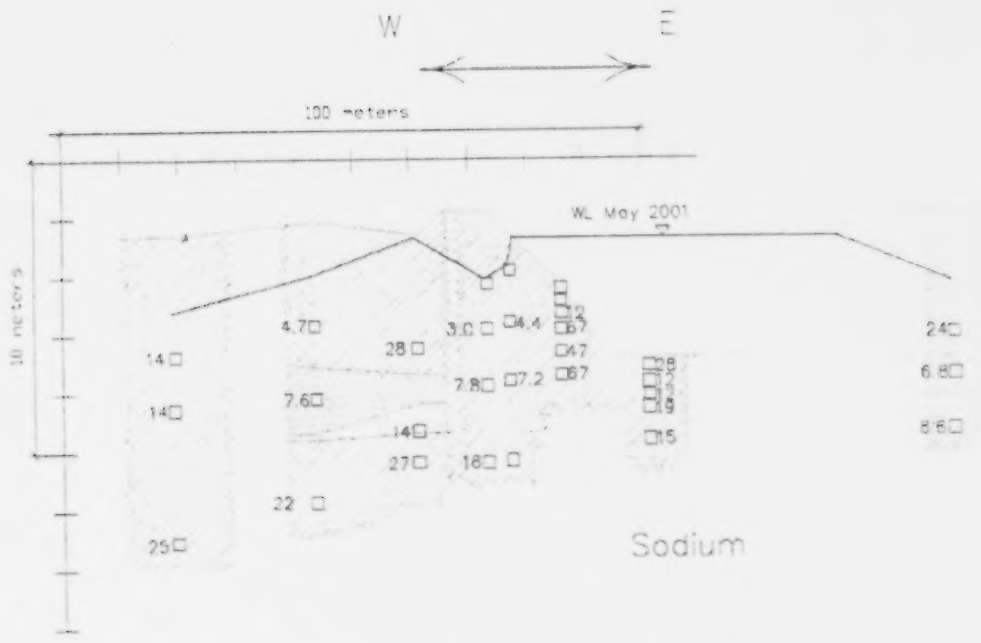

Figure 70. Site B, cell no. 1 sodium concentrations (meq/L) from May 2001.

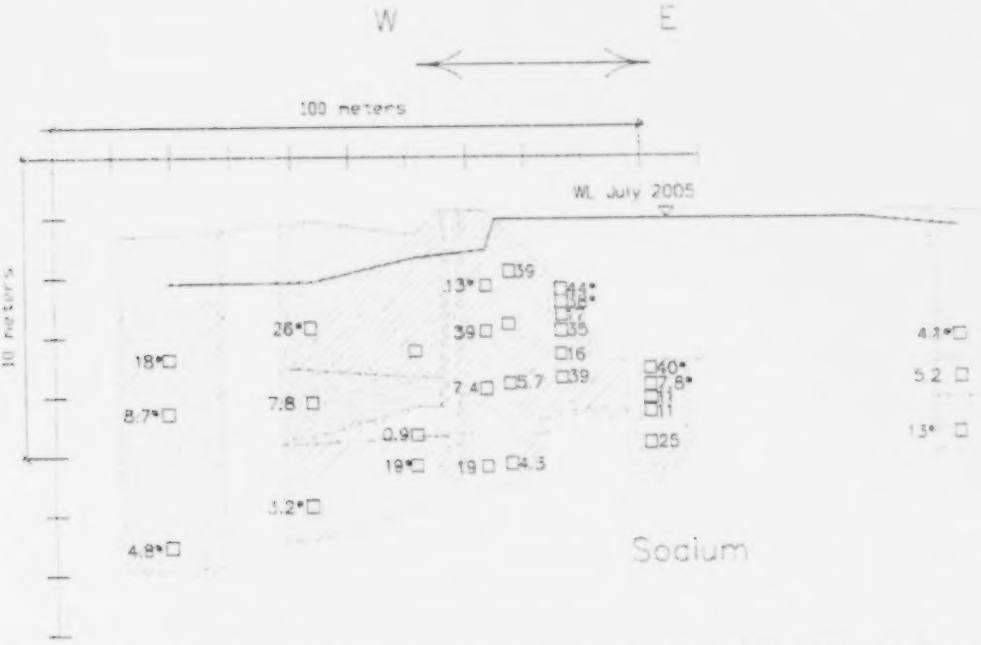

Figure 71. Site B, cell no. 1 sodium concentrations (meq/L) from July 2005. *Indicates a value from 2004, as 2005 data was not available.

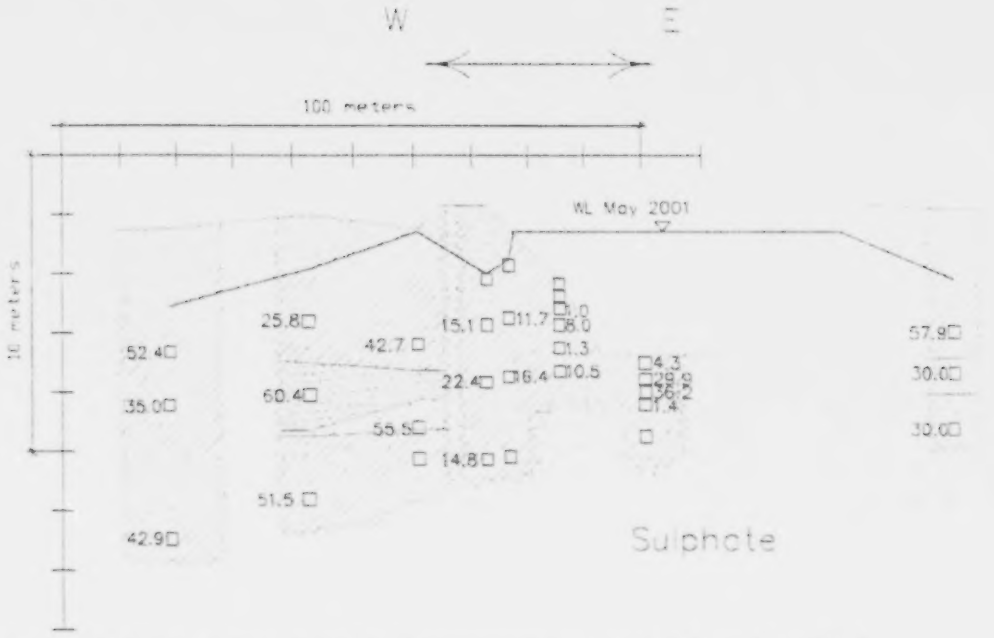

Figure 72. Site B, cell no. 1 sulphate concentrations (meq/L) from May 2001.

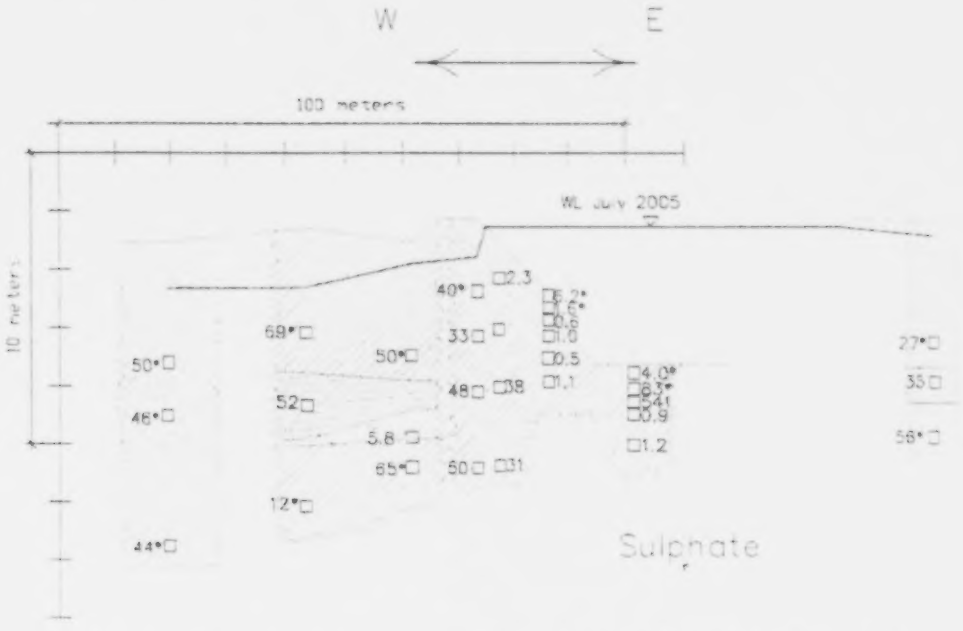

Figure 73. Site B, cell no. 1 sulphate concentrations (meq/L) from July 2005. *Indicates a value from 2004, as 2005 data was not available.

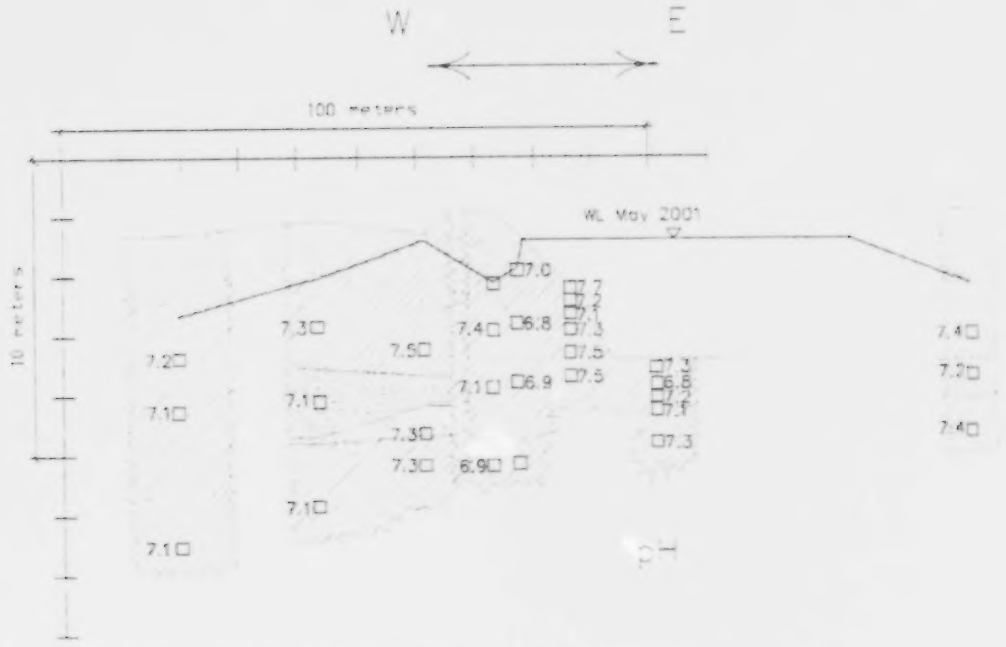

Figure 74. Site B, cell no. 1 pH readings from May 2001.

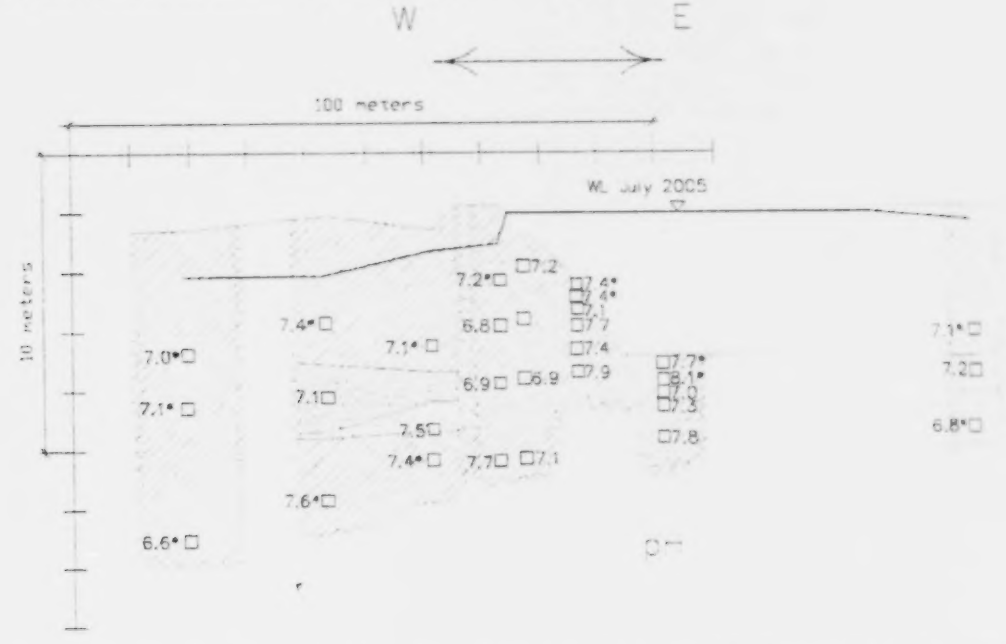

Figure 75. Site B, cell no. 1 pH readings from July 2005. *Indicates a value from 2004, as 2005 data was not available.

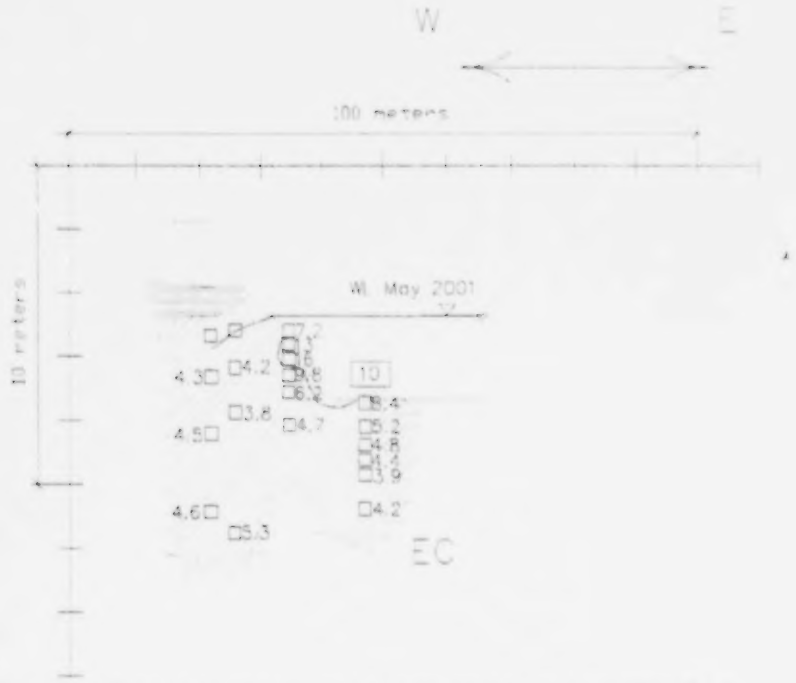

Figure 76. Site B, cell no. 2 electrical conductivity (mS/cm) from May 2001.

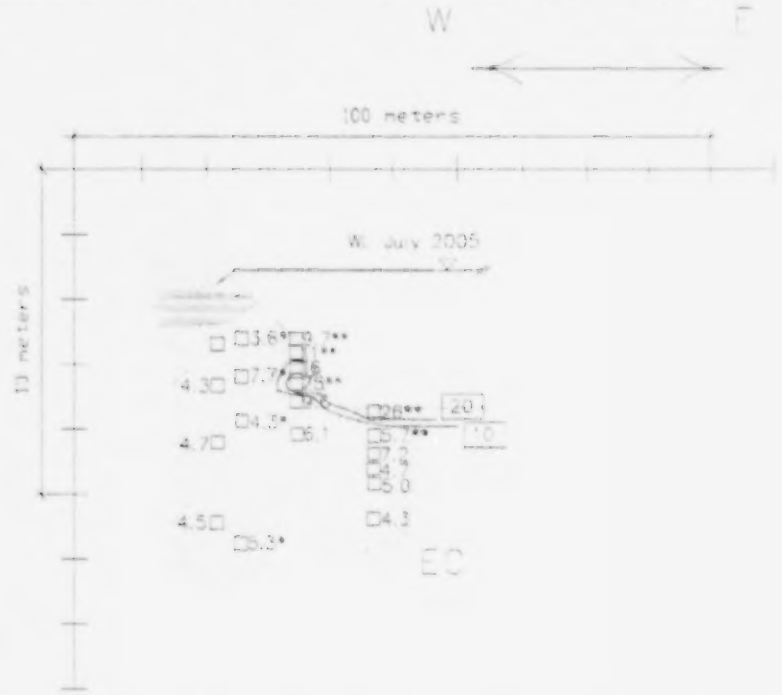

Figure 77. Site B, cell no. 2 electrical conductivity readings (mS/cm) from July 2005. *Indicates a value from 2004, as 2005 data was not available. ** Indicates a value from 2003, as 2004 data was not available.

Figure 78. Site B, cell no. 2 chloride concentrations (meq/L) from May 2001.

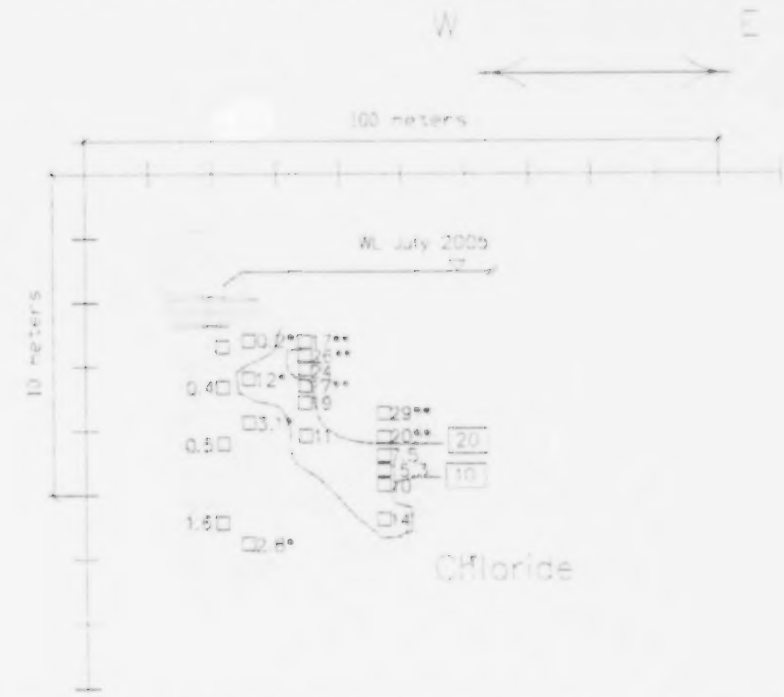

Figure 79. Site B, cell no. 2 chloride concentrations (meq/L) from July 2005. *Indicates a value from 2004, as 2005 data was not available. ** Indicates a value from 2003, as 2004 data was not available.

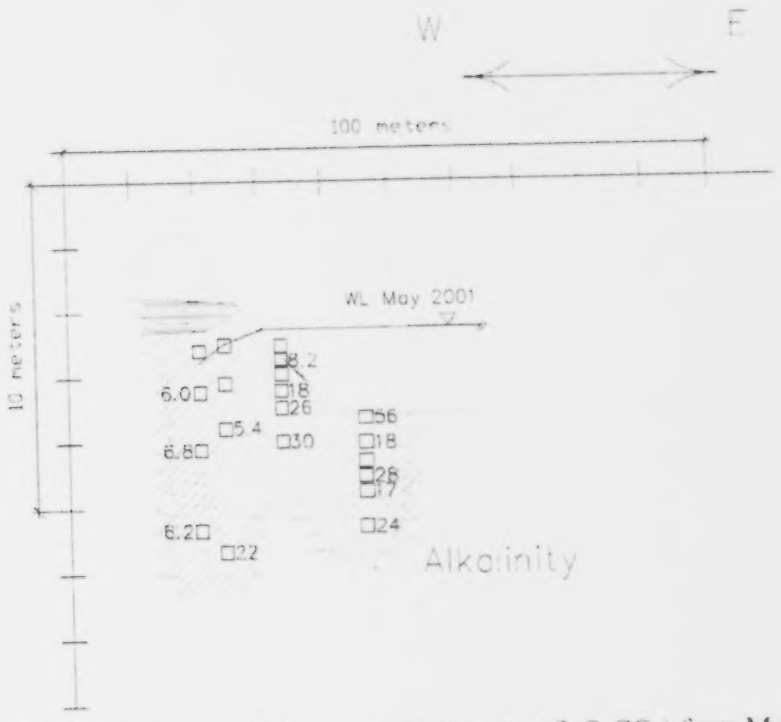

Figure 80. Site B, cell no. 2 alkalinity concentrations (meq/L $CaCO_3$) from May 2001.

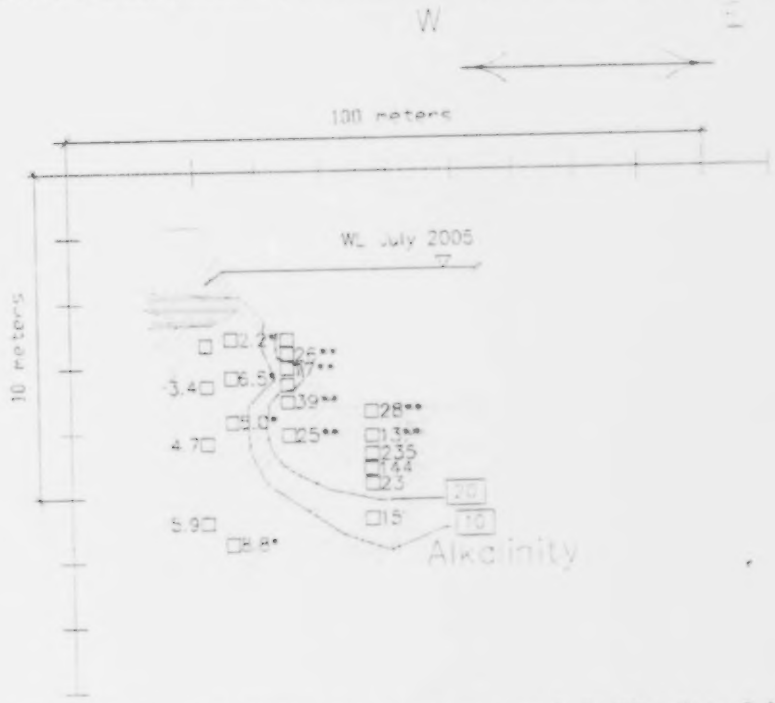

Figure 81. Site B, cell no. 2 alkalinity concentrations (meq/L $CaCO_3$) from July 2005. *Indicates a value from 2004, as 2005 data was not available. ** Indicates a value from 2003, as 2004 data was not available.

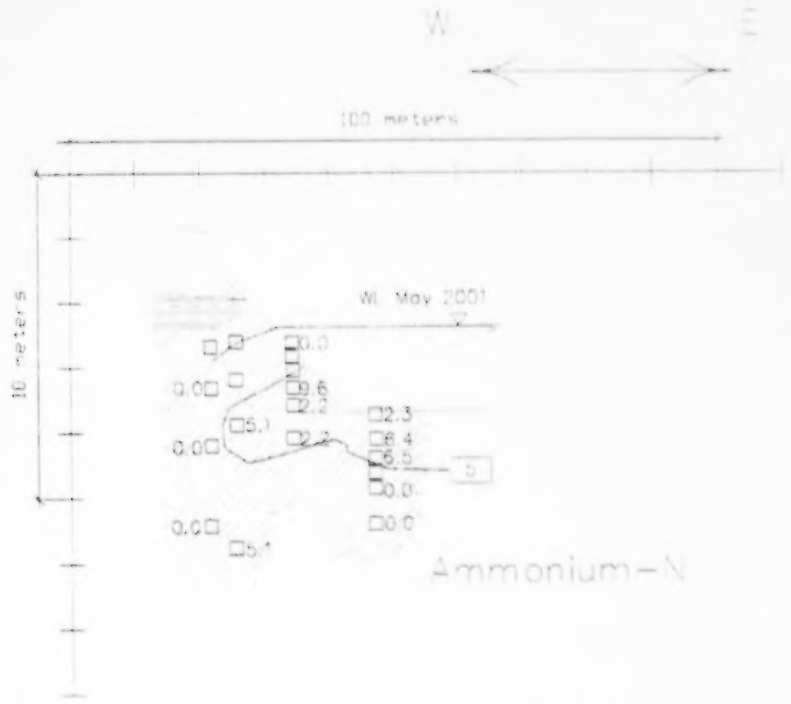

Figure 82. Site B, cell no. 2 ammonium concentrations (meq/L) from May 2001.

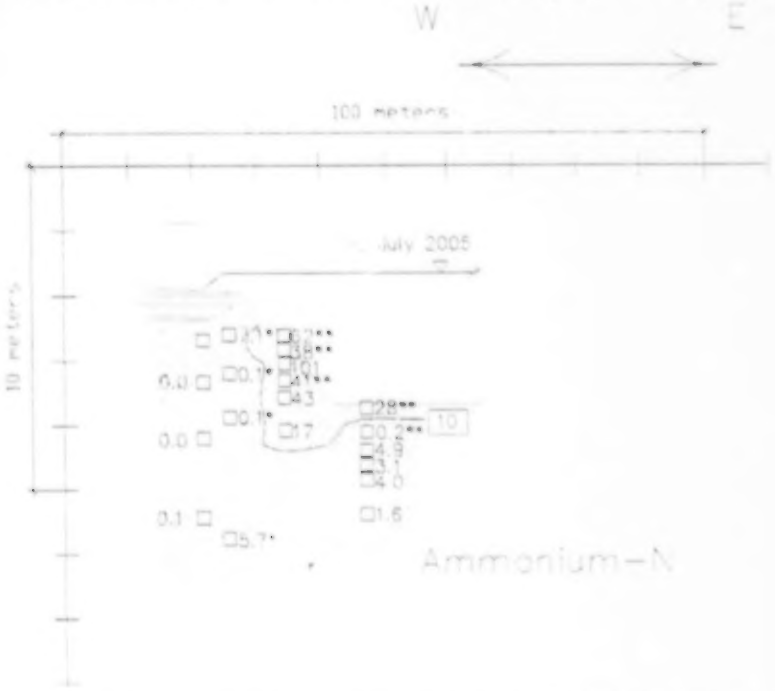

Figure 83. Site B, cell no. 2 ammonium concentrations (meq/L) from July 2005. *Indicates a value from 2004, as 2005 data was not available. ** Indicates a value from 2003, as 2004 data was not available.

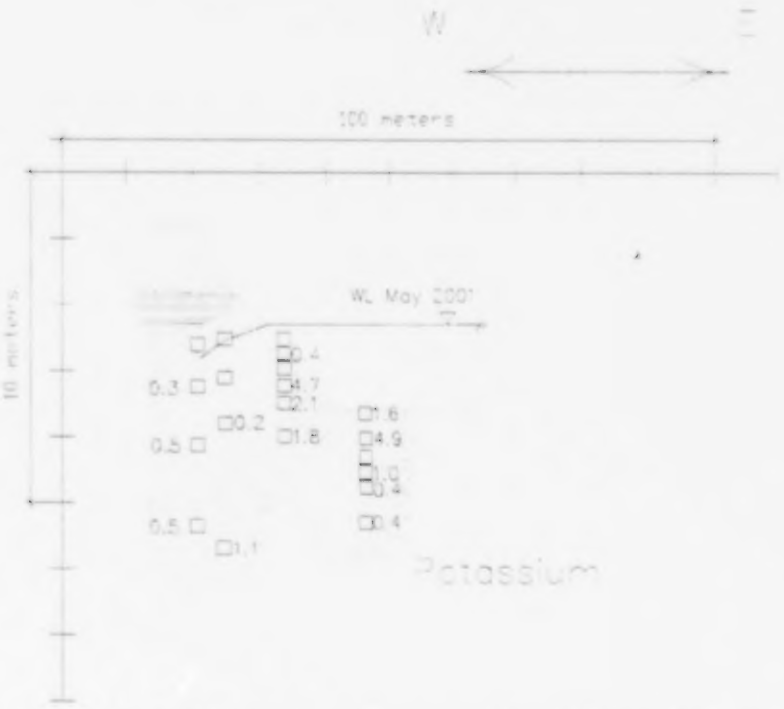

Figure 84. Site B, cell no. 2 potassium concentrations (meq/L) from May 2001.

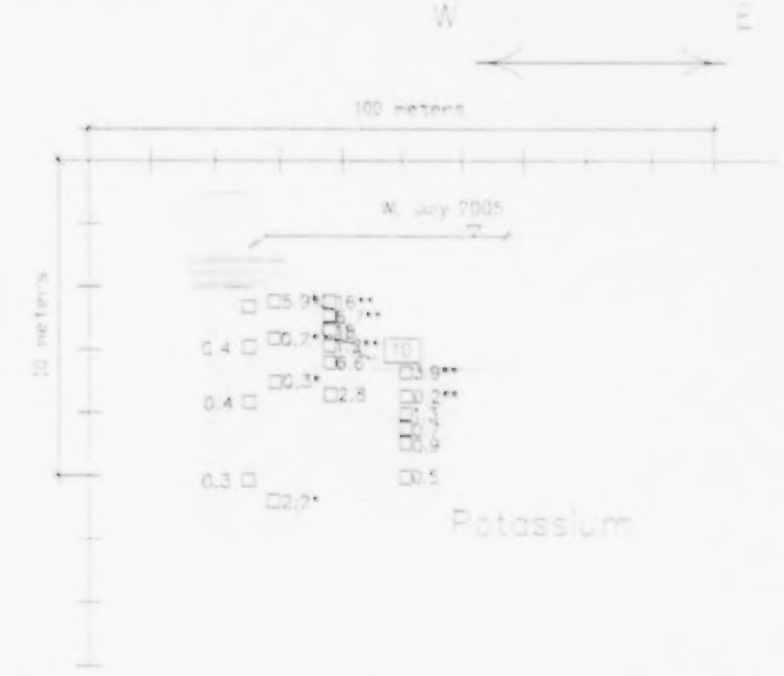

Figure 85. Site B, cell no. 2 potassium concentrations (meq/L) from July 2005.
*Indicates a value from 2004, as 2005 data was not available. ** Indicates a value from 2003, as 2004 data was not available.

Figure 86. Site B. cell no. 2 magnesium concentrations (meq/L) from May 2001.

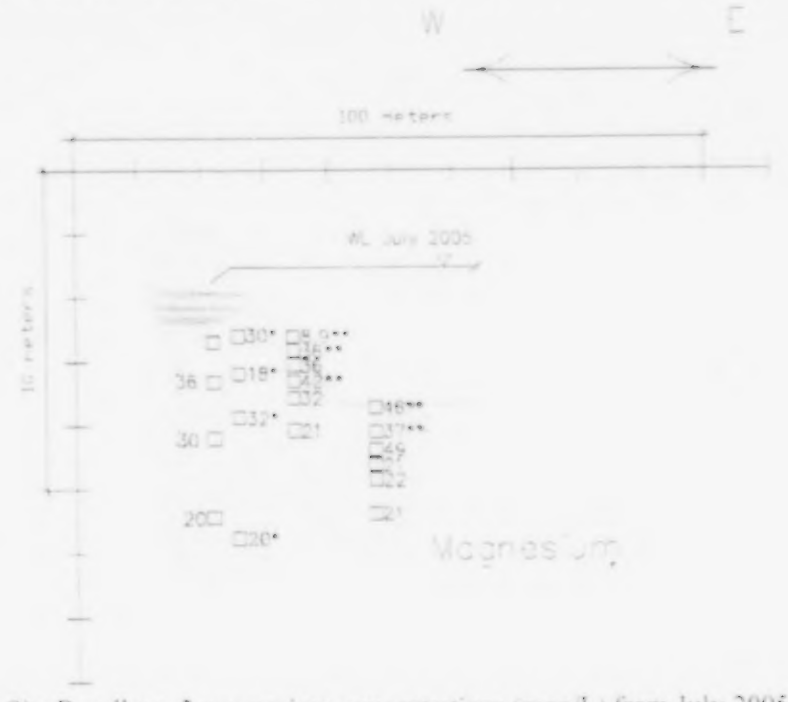

Figure 87. Site B. cell no. 2 magnesium concentrations (meq/L) from July 2005.
*Indicates a value from 2004, as 2005 data was not available. ** Indicates a value from 2003, as 2004 data was not available.

Figure 88. Site B, cell no. 2 calcium concentrations (meq/L) from May 2001.

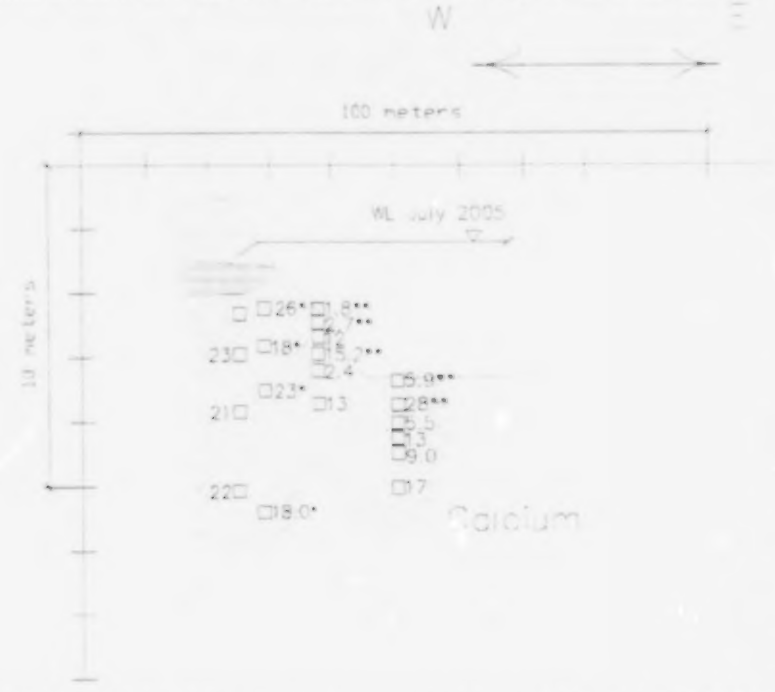

Figure 89. Site B, cell no. 2 calcium concentrations (meq/L) from July 2005. *Indicates a value from 2004, as 2005 data was not available. ** Indicates a value from 2003, as 2004 data was not available.

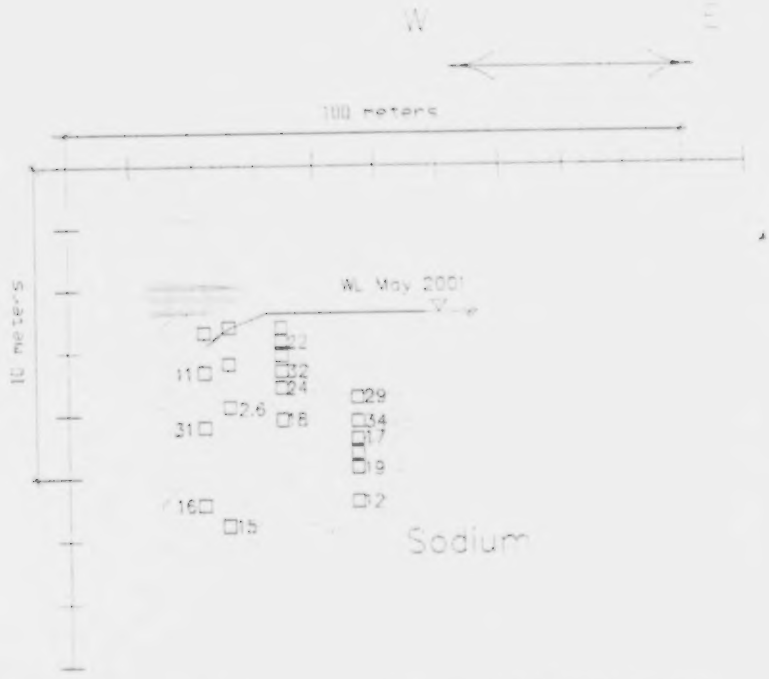

Figure 90. Site B, cell no. 2 sodium concentrations (meq/L) from May 2001.

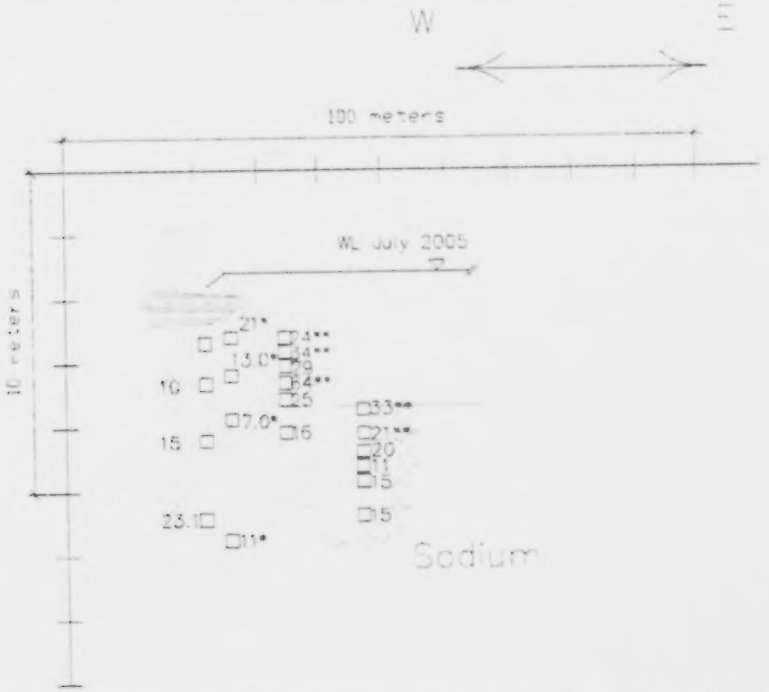

Figure 91. Site B, cell no. 2 sodium concentrations (meq/L) from July 2005. *Indicates a value from 2004, as 2005 data was not available. ** Indicates a value from 2003, as 2004 data was not available.

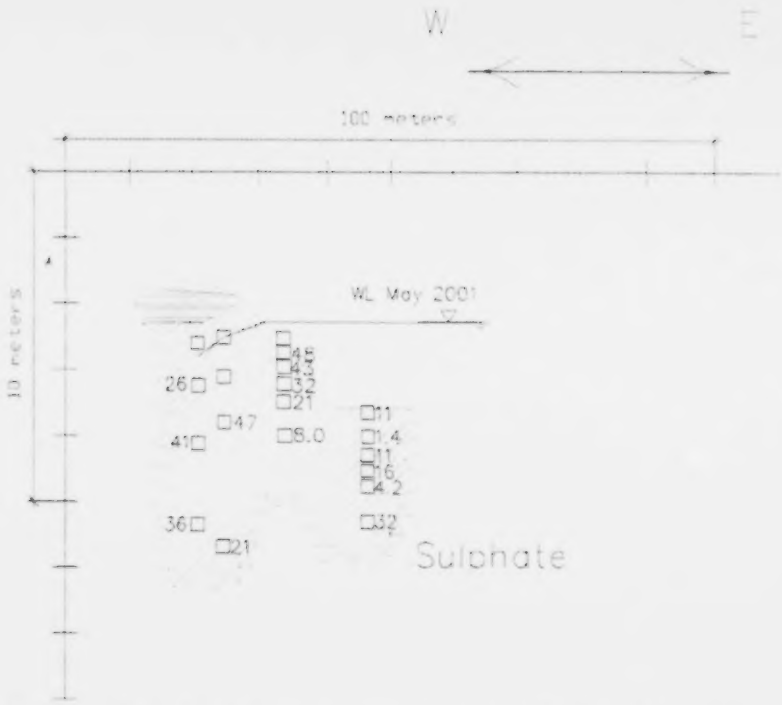

Figure 92. Site B. cell no. 2 sulphate concentrations (meq/L) from May 2001.

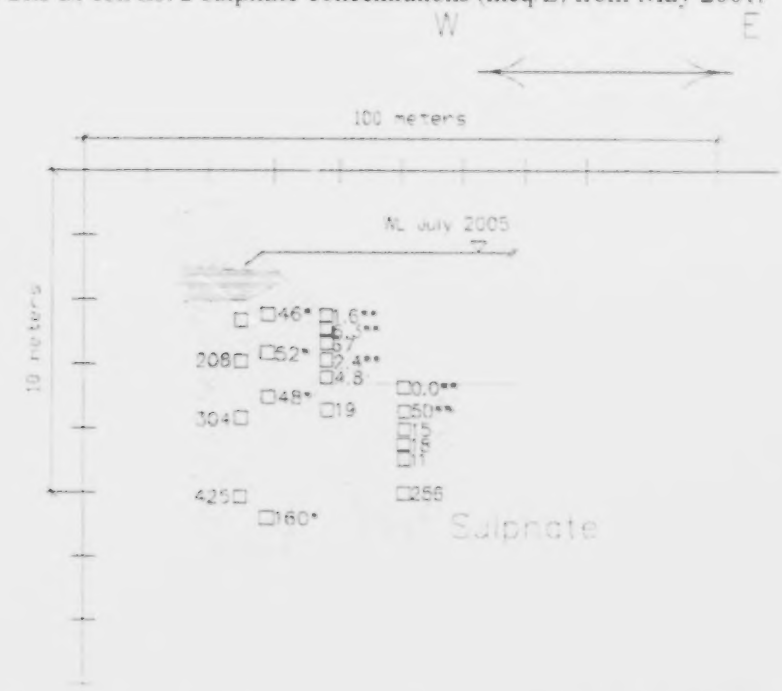

Figure 93. Site B. cell no. 2 sulphate concentrations (meq/L) from July 2005. *Indicates a value from 2004, as 2005 data was not available. ** Indicates a value from 2003, as 2004 data was not available.

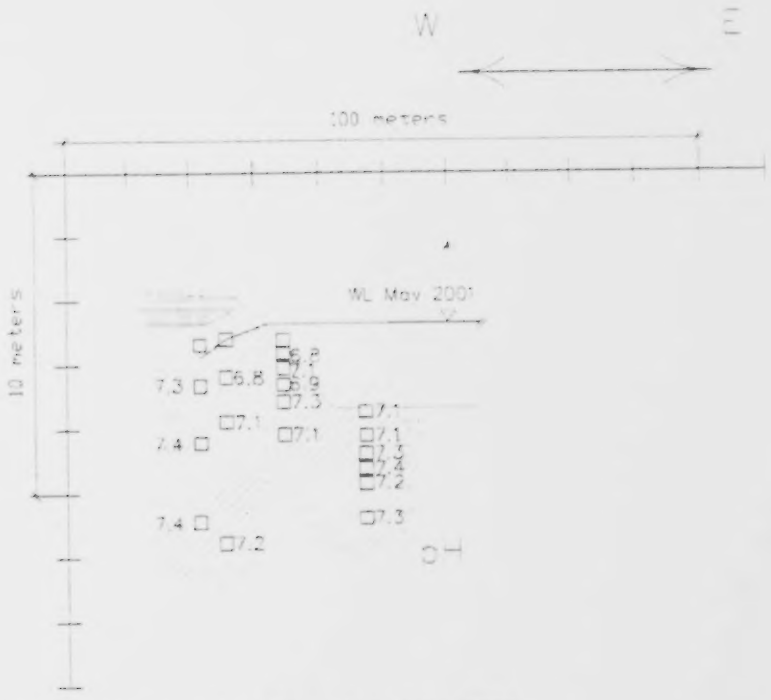

Figure 94. Site B. cell no. 2 pH readings from May 2001.

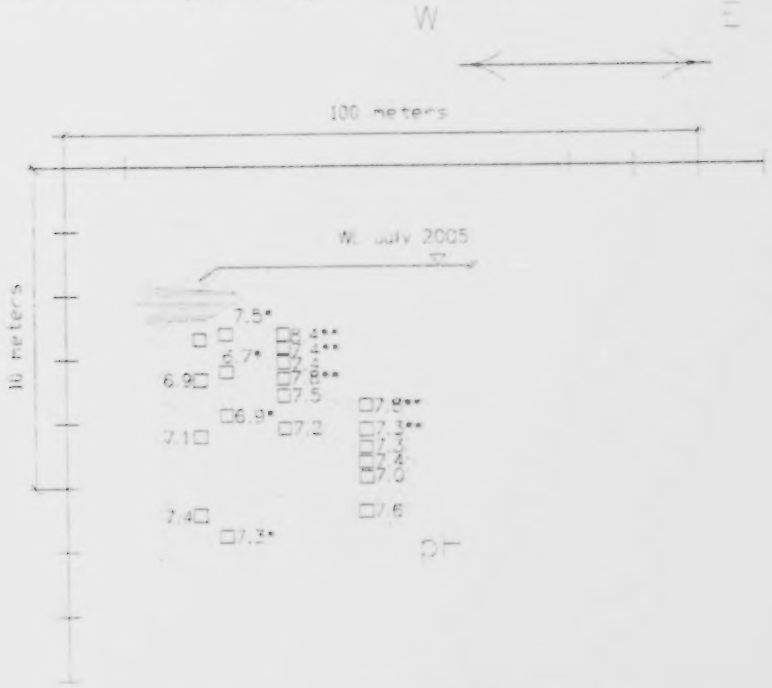

Figure 95. Site B. cell no. 2 pH readings from July 2005. *Indicates a value from 2004, as 2005 data was not available. ** Indicates a value from 2003, as 2004 data was not available.

Site C

Figures 81 to 120 show geologic sections of the site with concentration profiles for electrical conductivity, chloride, alkalinity, ammonium, potassium, magnesium, calcium, sodium, sulphate and pH in June 2001 and September 2005.

In 2005, elevated ion concentrations greater than 10 meq/L are indicated to depths of 0.3 to 0.5 metres below Cell No. 1 and extend to the west approximately 6 metres from the toe of the inside side slope. Elevated ion concentrations do not appear to extend more than 3 metres adjacent to the mid point of the inside side slopes. This transport pattern is indicated by elevated concentrations of chloride, ammonium, potassium, reduced levels of sulphate and electrical conductivity readings. Alkalinity appears to be elevated to depths of at least 3 metres below the storage but may not be a direct result of EMS seepage. Similarly, sulphate and magnesium concentrations are significantly elevated to depths of approximately 5 metres below the storage floor elevation and approximately 12 to 15 metres west of the midpoint of the inside side slope of the storage. These elevated levels of sulphate and magnesium may be the result of gypsum dissolution as a result of increased ionic strength and/or release of magnesium from exchange sites as a result of calcium exchange and/or potassium and ammonium attenuation.

Cell No. 2 at this site was empty for approximately 18 months following construction. This may have affected the hydraulic conductivity of the base liner as compared to Cell No. 1. Elevated ion concentrations (greater than10 meq/L) are indicated to depths of three metres below the cell and 3 to 8 metres adjacent to the top and toe of the inside side slope respectively. This pattern is indicated by elevated concentrations of chloride and sodium, sulphate reduction and elevated electrical conductivity readings. Ammonium, potassium, magnesium and calcium concentrations appear to follow the chromatographic series reported by Fonstad (2004) from results of a complimentary study. Potassium is attenuated with respect to chloride with elevated concentrations indicated at depths of 0.3 to 0.5 metres below the storage. Ammonium is slightly less attenuated due to its inability to compete with high concentrations of potassium (Dance and Reardon 1983; Fonstad 2004). The result of the attenuation of potassium and ammonium is the release of magnesium and calcium from exchange sites as indicated by magnesium and calcium concentrations at a depth of 1 to 1.5 metres below the storage of approximately 2 to 3 times the background or adjacent concentrations.

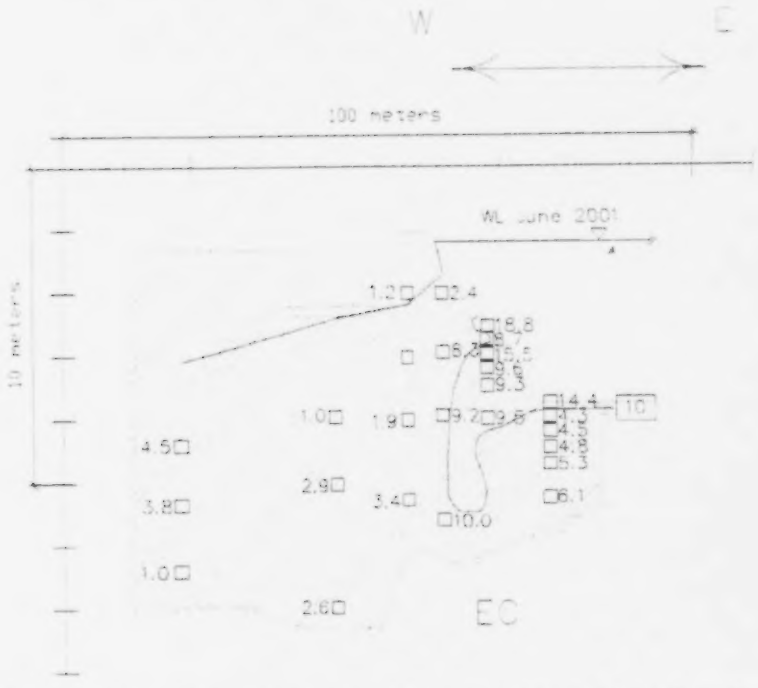

Figure 96. Site C, cell no. 1 electrical conductivity readings (mS/cm) from June 2001.

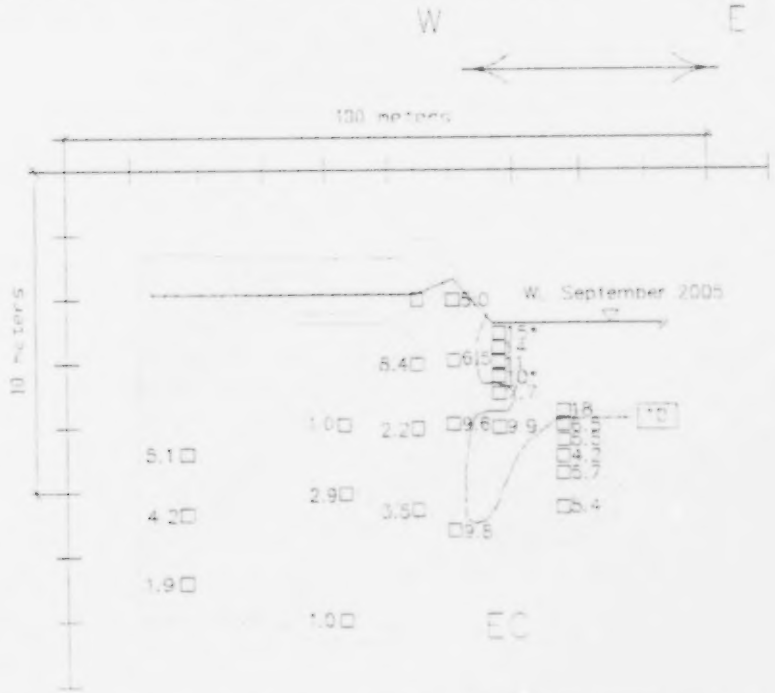

Figure 97. Site C, cell no. 1 electrical conductivity reading (mS/cm) from July 2005. *Indicates a value from 2004, as 2005 data was not available. ** Indicates a value from 2003, as 2004 data was not available.

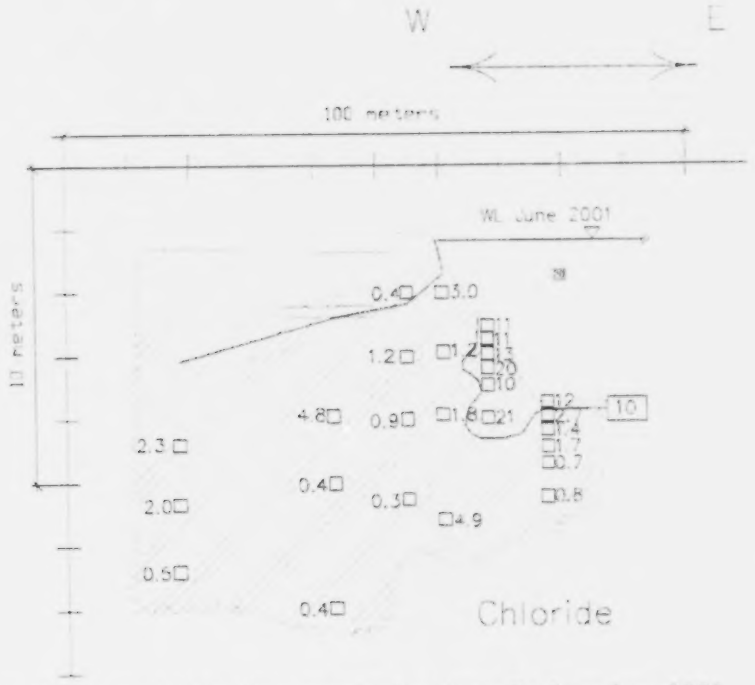

Figure 98. Site C, cell no. 1 chloride concentrations (meq/L) from June 2001.

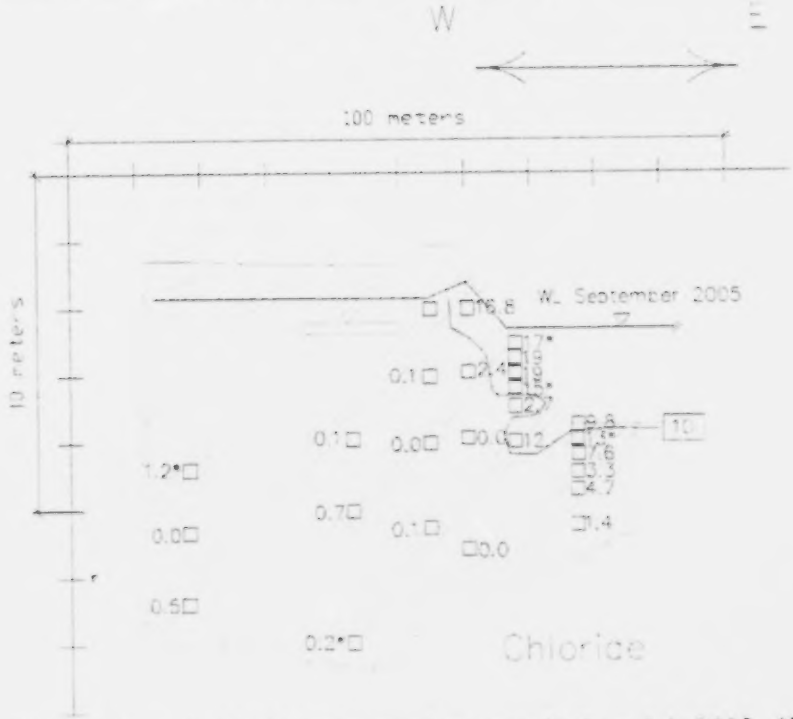

Figure 99. Site C, cell no. 1 chloride concentrations (meq/L) from July 2005. *Indicates a value from 2004, as 2005 data was not available. ** Indicates a value from 2003, as 2004 data was not available.

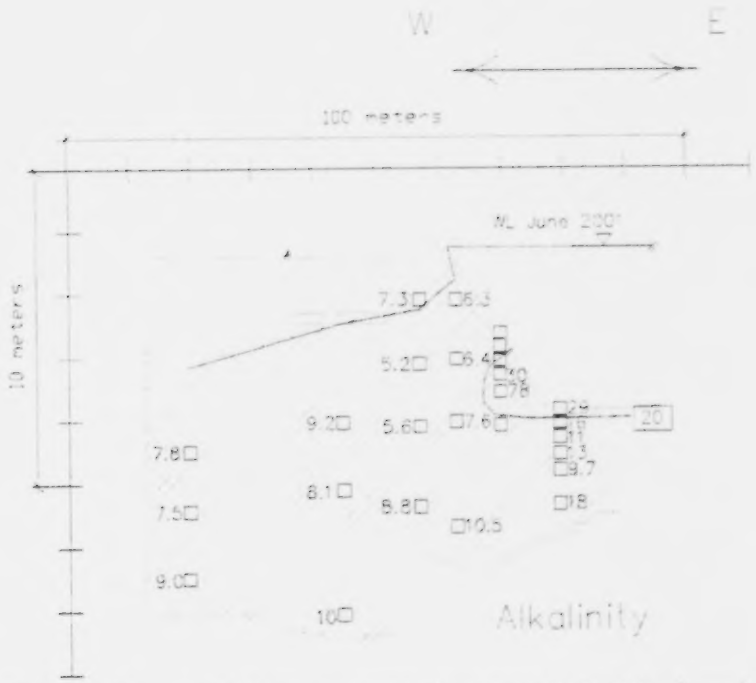

Figure 100. Site C, cell no. 1 alkalinity concentrations (meq/L $CaCO_3$) from June 2001.

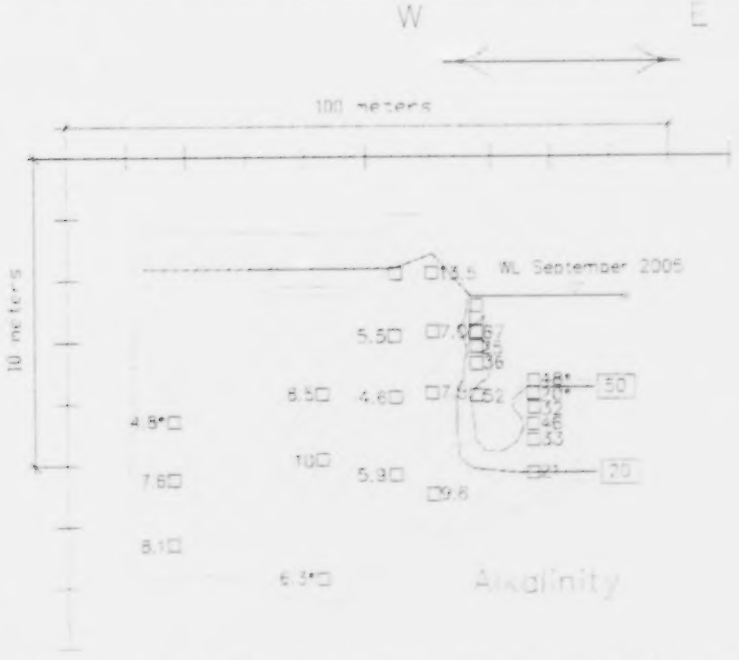

Figure 101. Site C, cell no. 1 alkalinity concentrations (meq/L $CaCO_3$) from July 2005. *Indicates a value from 2004, as 2005 data was not available. ** Indicates a value from 2003, as 2004 data was not available.

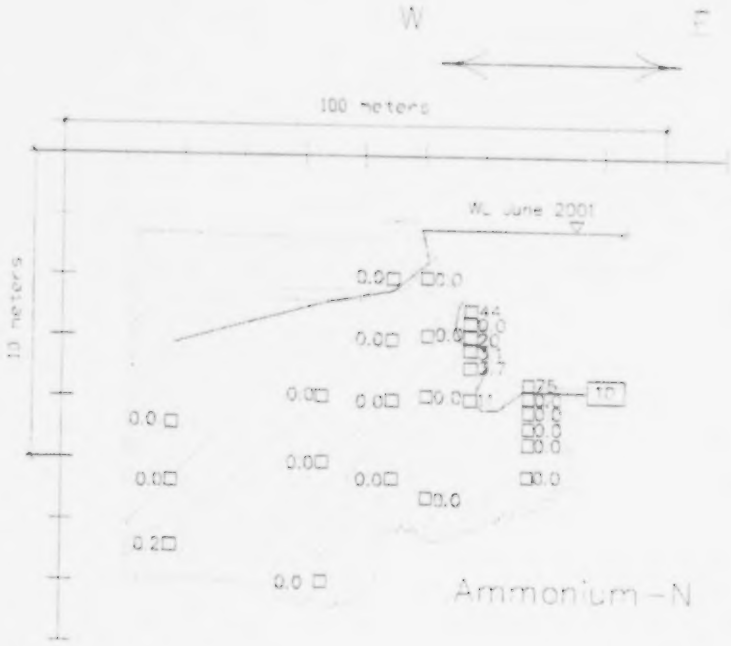

Figure 102. Site C, cell no. 1 ammonium concentrations (meq/L) from June 2001.

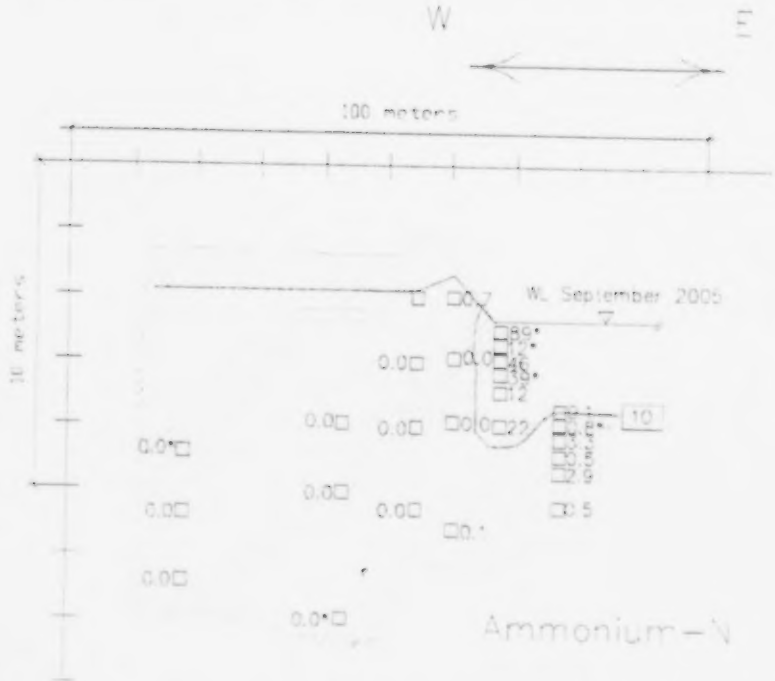

Figure 103. Site C, cell no. 1 ammonium concentrations (meq/L) from July 2005. *Indicates a value from 2004, as 2005 data was not available. ** Indicates a value from 2003, as 2004 data was not available.

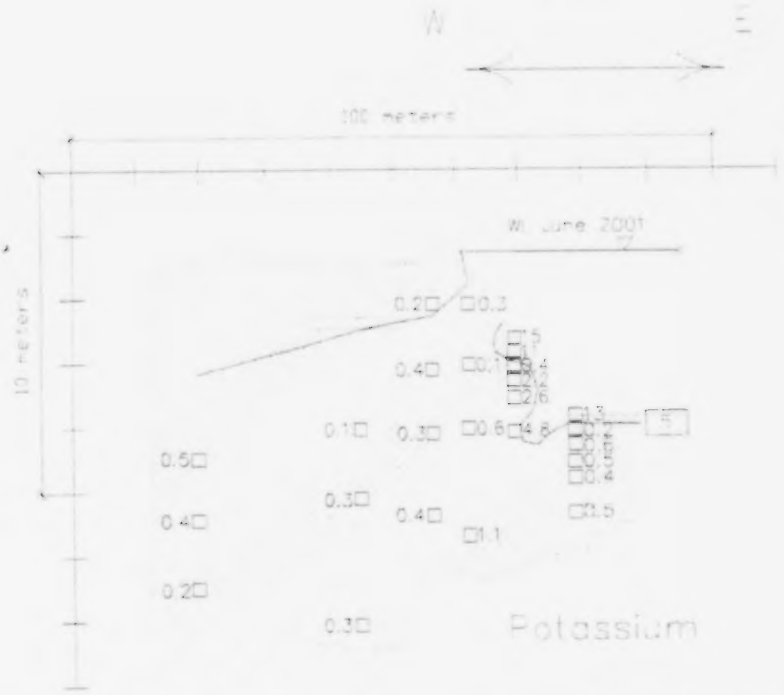

Figure 104. Site C, cell no. 1 potassium concentrations (meq/L) from June 2001.

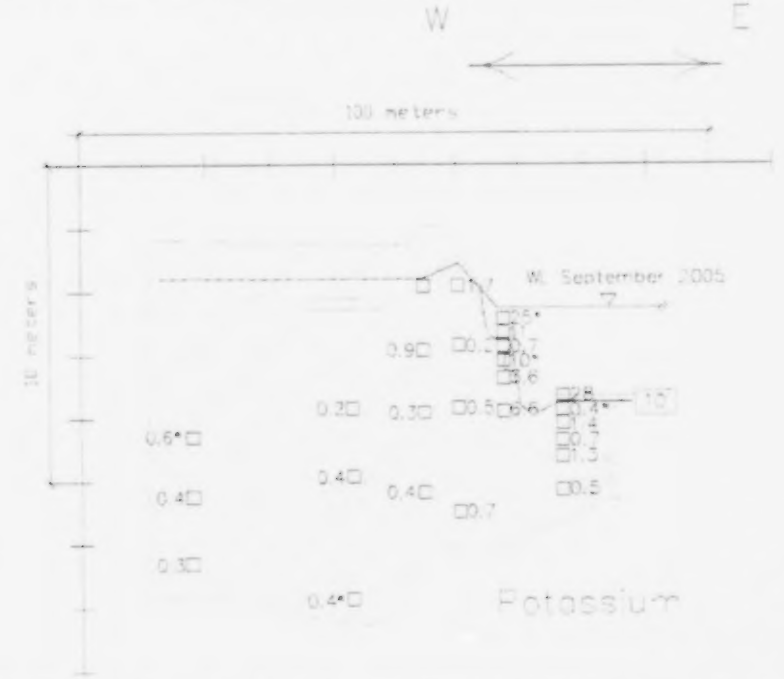

Figure 105. Site C, cell no. 1 potassium concentrations (meq/L) from July 2005.
*Indicates a value from 2004, as 2005 data was not available. ** Indicates a value from 2003, as 2004 data was not available.

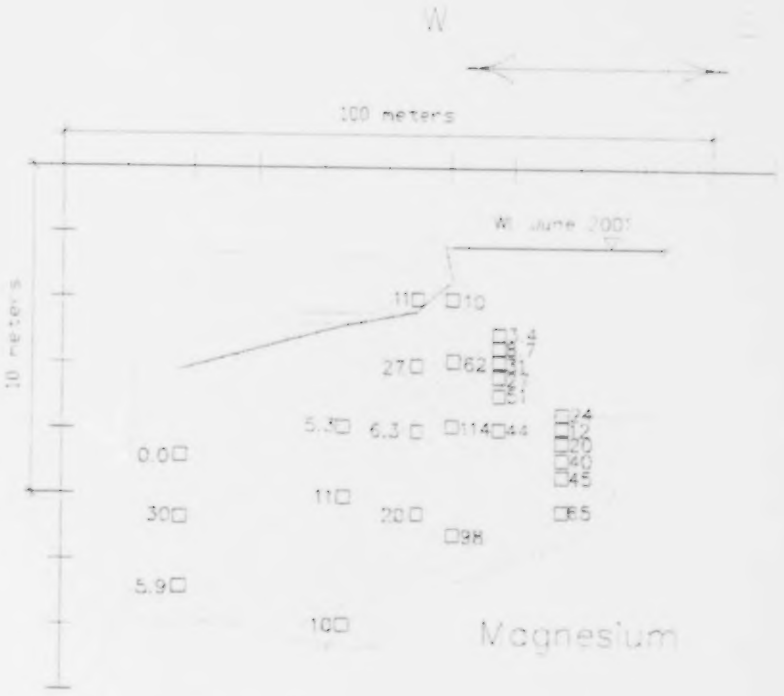

Figure 106. Site C, cell no. 1 magnesium concentrations (meq/L) from June 2001.

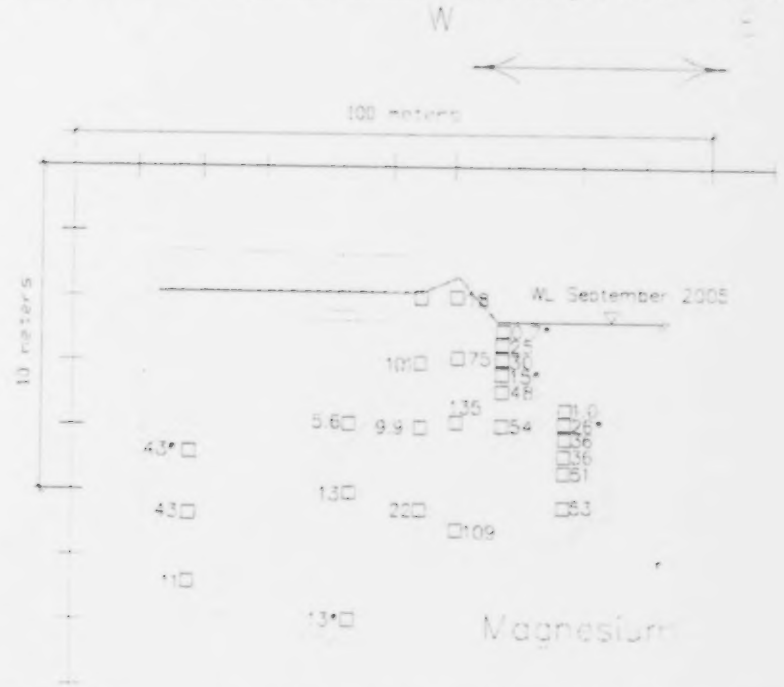

Figure 107. Site C, cell no. 1 magnesium concentrations (meq/L) from July 2005.
*Indicates a value from 2004, as 2005 data was not available. ** Indicates a value from 2003, as 2004 data was not available.

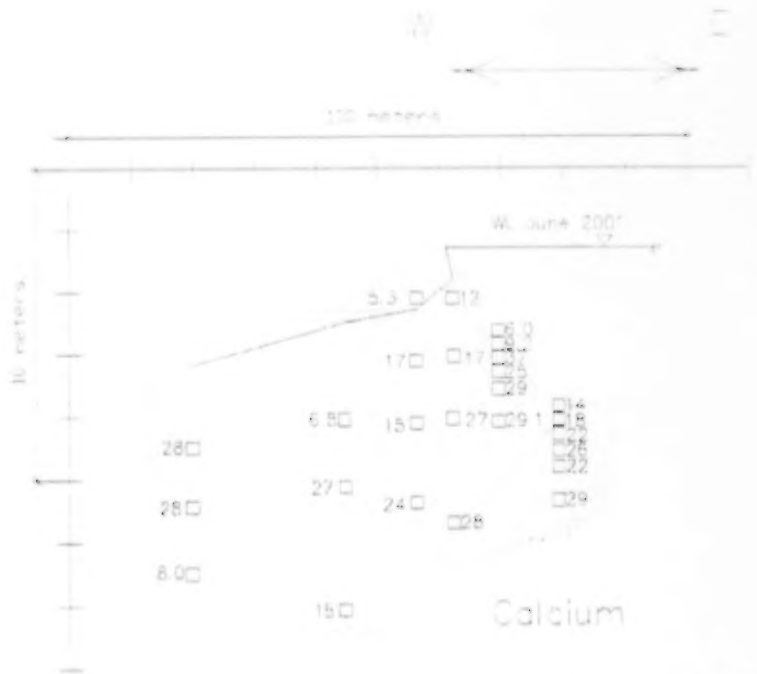

Figure 108. Site C, cell no. 1 calcium concentrations (meq/L) from June 2001.

Figure 109. Site C, cell no. 1 calcium concentrations (meq/L) from July 2005. *Indicates a value from 2004, as 2005 data was not available. ** Indicates a value from 2003, as 2004 data was not available.

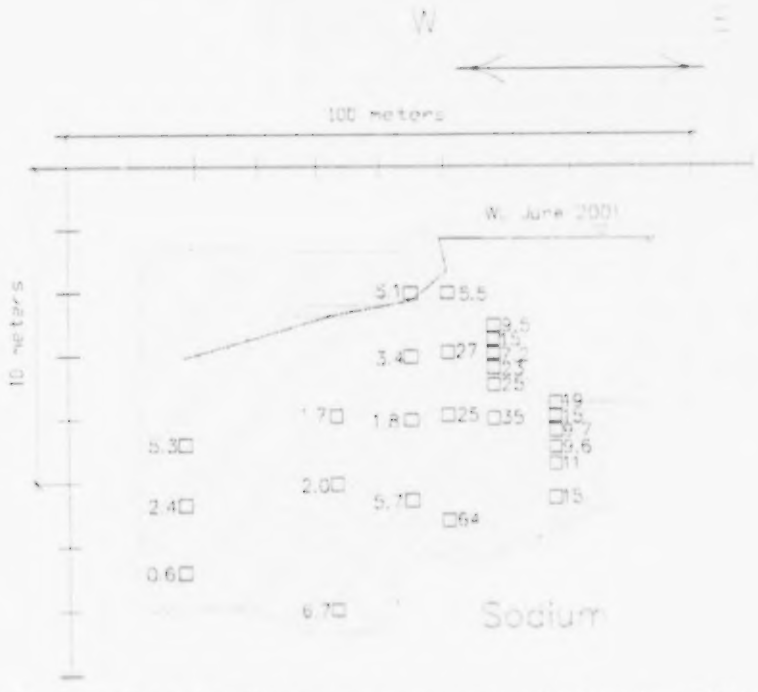

Figure 110. Site C, cell no. 1 sodium concentrations (meq/L) from June 2001.

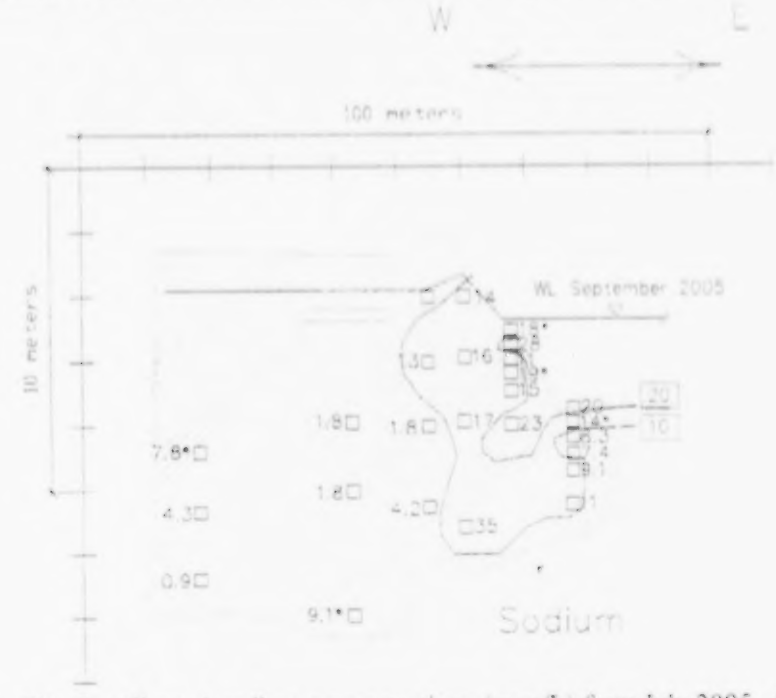

Figure 111. Site C, cell no. 1 sodium concentrations (meq/L) from July 2005. *Indicates a value from 2004, as 2005 data was not available. ** Indicates a value from 2003, as 2004 data was not available.

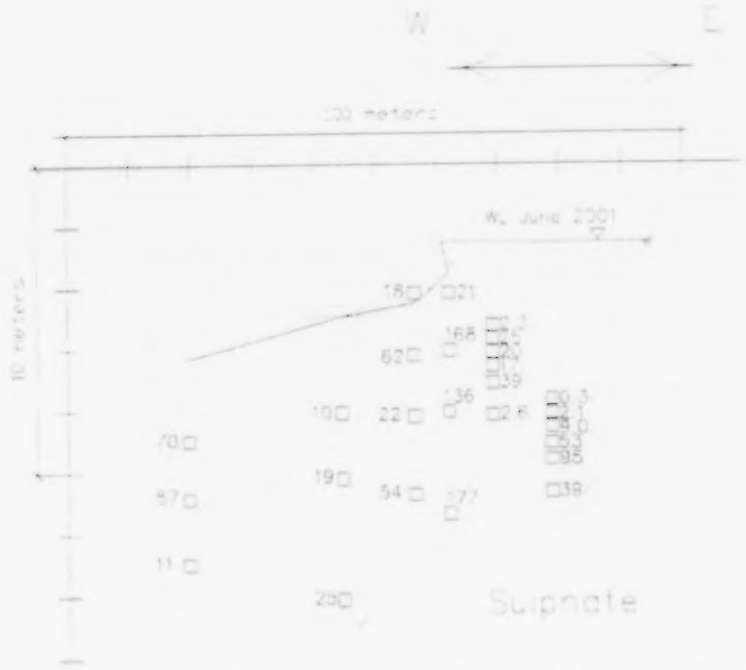

Figure 112. Site C, cell no. 1 sulphate concentrations (meq/L) from June 2001.

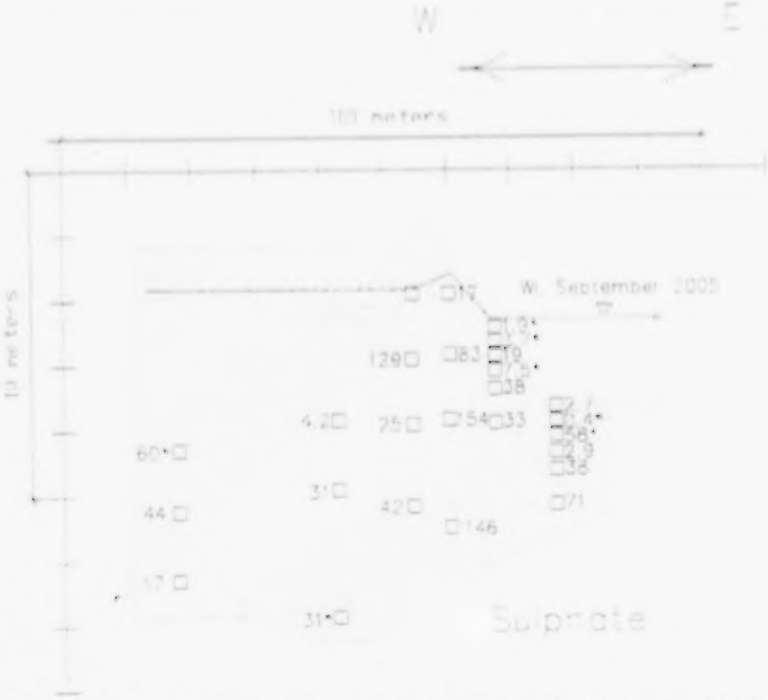

Figure 113. Site C, cell no. 1 sulphate concentrations (meq/L) from July 2005. *Indicates a value from 2004, as 2005 data was not available. ** Indicates a value from 2003, as 2004 data was not available.

Figure 114. Site C, cell no. 1 pH readings from June 2001.

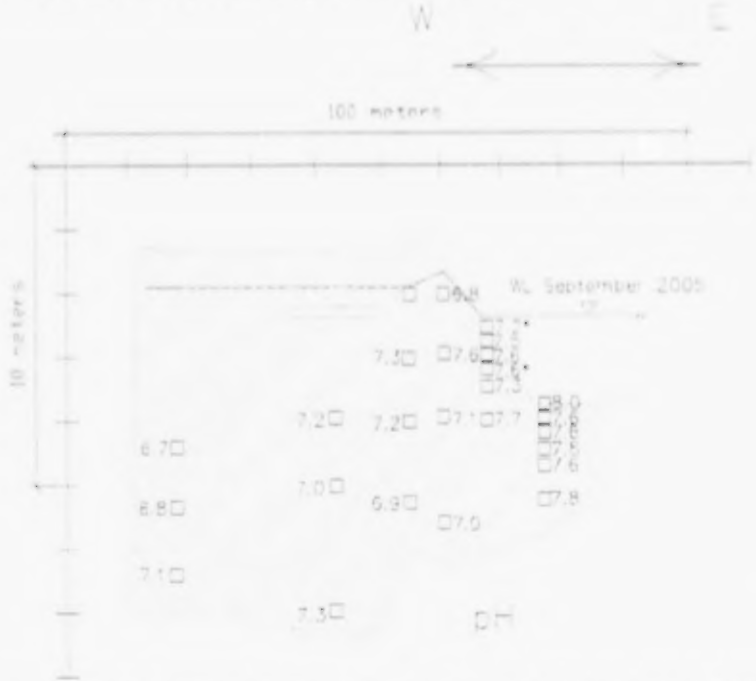

Figure 115. Site C, cell no. 1 pH readings from July 2005. *Indicates a value from 2004, as 2005 data was not available. ** Indicates a value from 2003, as 2004 data was not available.

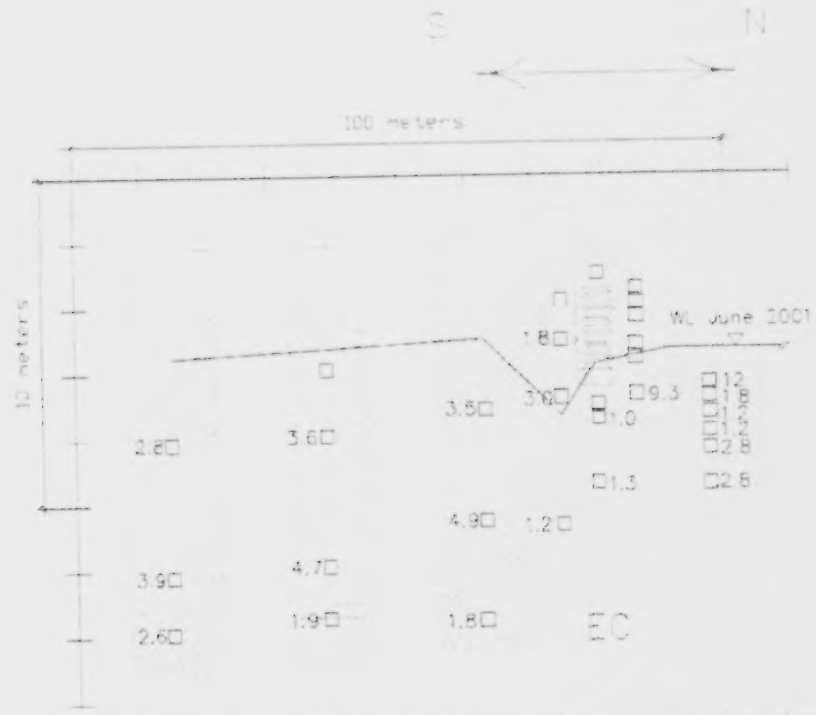

Figure 116. Site C, cell no. 2 electrical conductivity readings (mS/cm) from June 2001.

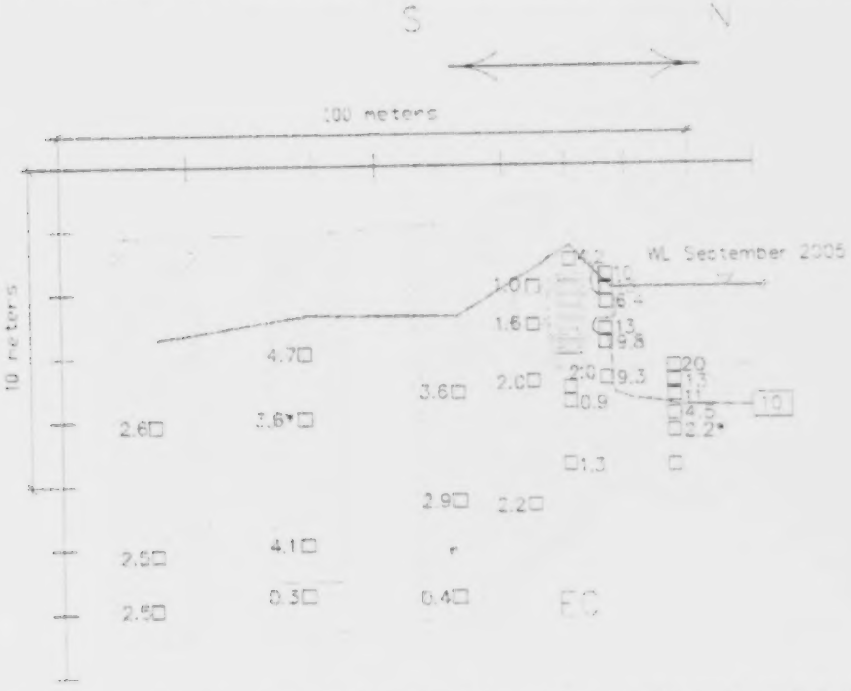

Figure 117. Site C, cell no. 2 electrical conductivity readings (mS/cm) from July 2005. *Indicates a value from 2004, as 2005 data was not available. ** Indicates a value from 2003, as 2004 data was not available.

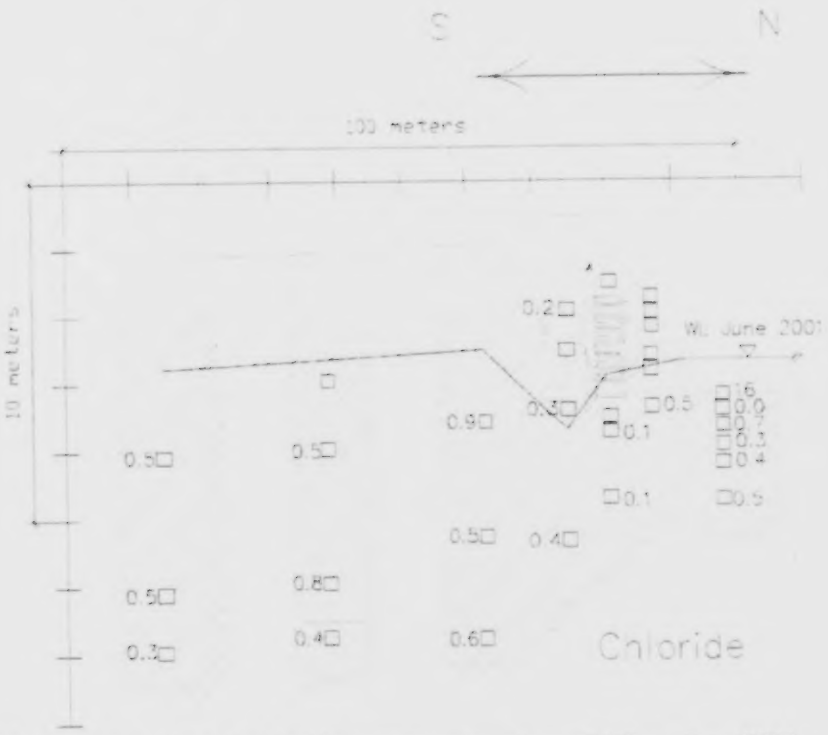

Figure 118. Site C, cell no. 2 chloride concentrations (meq/L) from June 2001.

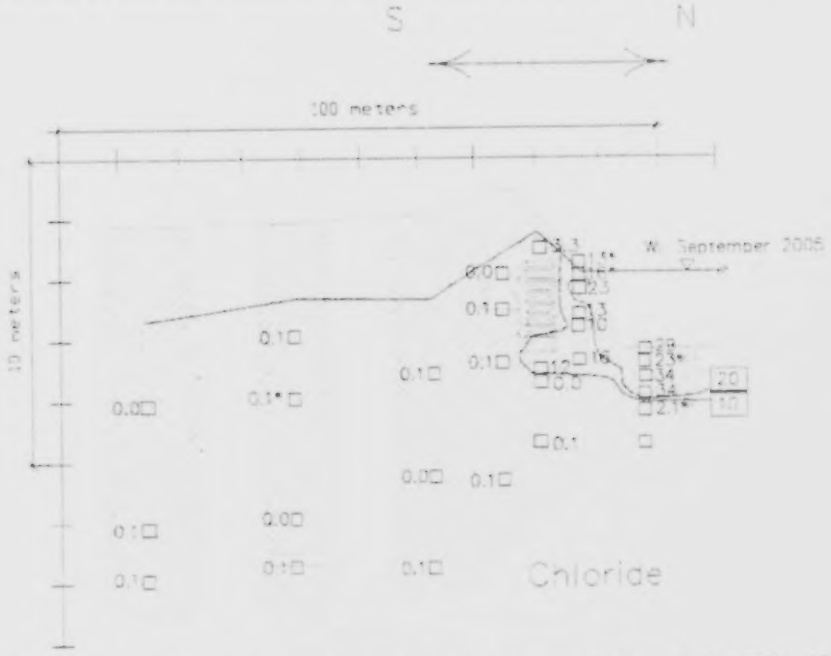

Figure 119. Site C, cell no. 2 chloride concentrations (meq/L) from July 2005. *Indicates a value from 2004, as 2005 data was not available. ** Indicates a value from 2003, as 2004 data was not available.

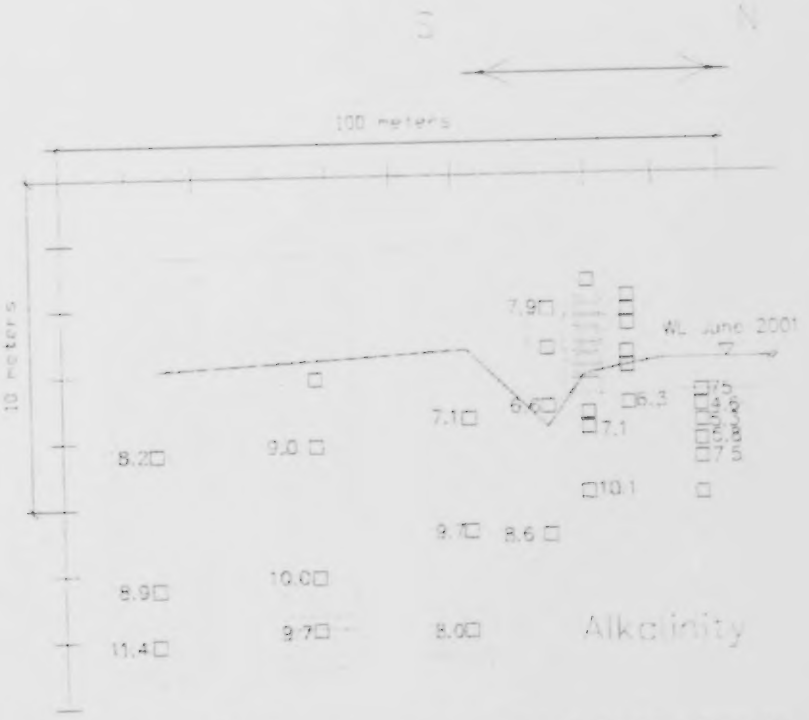

Figure 120. Site C, cell no. 2 alkalinity concentrations (meq/L $CaCO_3$) from June 2001.

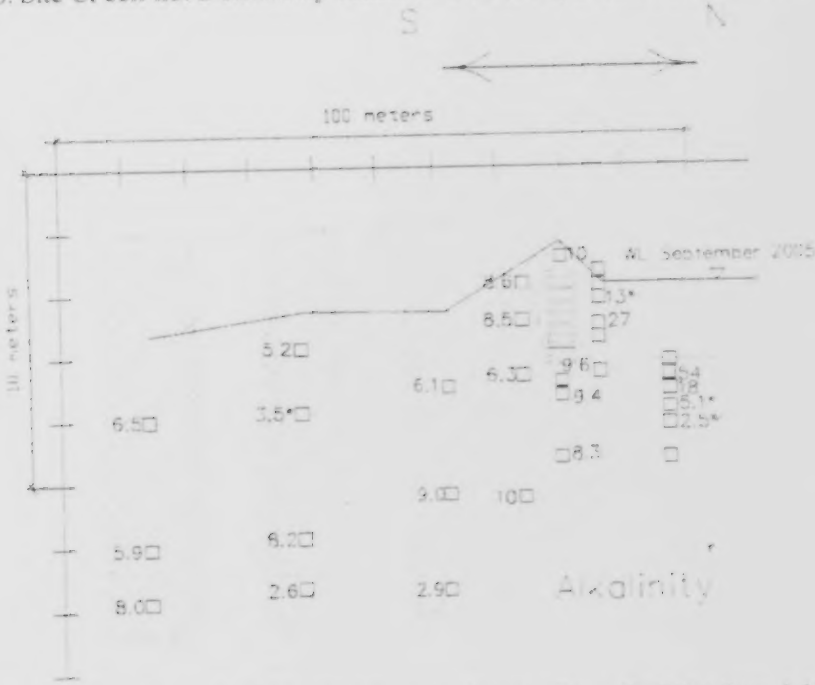

Figure 121. Site C, cell no. 2 alkalinity concentrations (mS/cm $CaCO_3$) from July 2005. *Indicates a value from 2004, as 2005 data was not available. ** Indicates a value from 2003, as 2004 data was not available.

Figure 122. Site C, cell no. 2 ammonium concentrations (meq/L N) from June 2001.

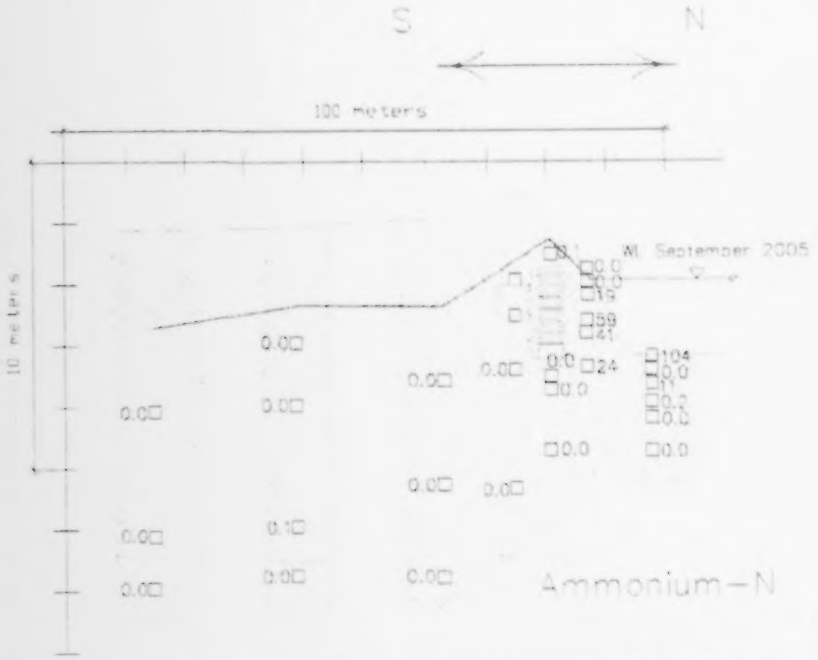

Figure 123. Site C, cell no. 2 ammonium concentrations (meq/L) from July 2005. *Indicates a value from 2004, as 2005 data was not available. ** Indicates a value from 2003, as 2004 data was not available.

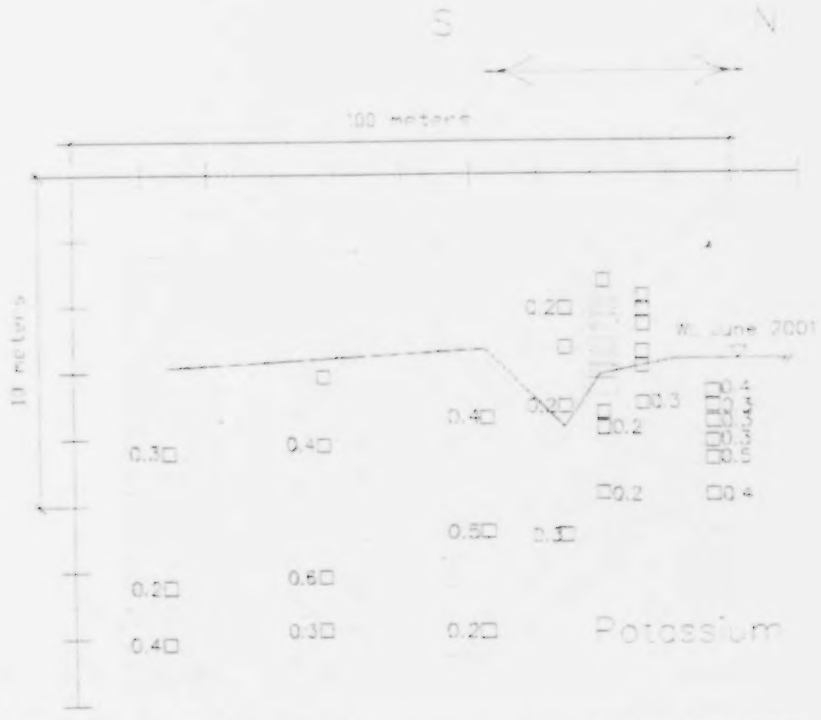

Figure 124. Site C, cell no. 2 potassium concentrations (meq/L) from June 2001.

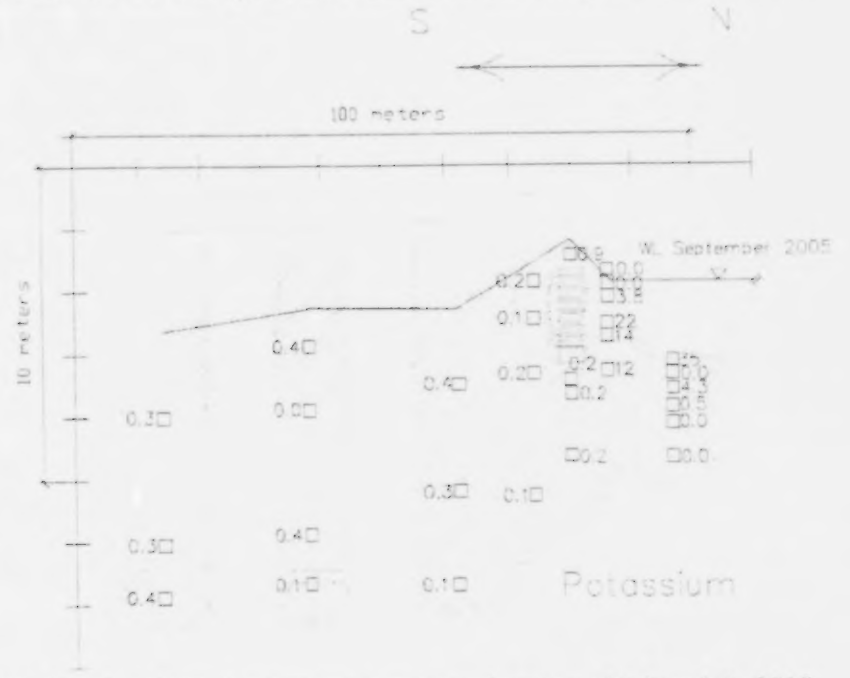

Figure 125. Site C, cell no. 2 potassium concentrations (meq/L) from July 2005.
*Indicates a value from 2004, as 2005 data was not available. ** Indicates a value from 2003, as 2004 data was not available.

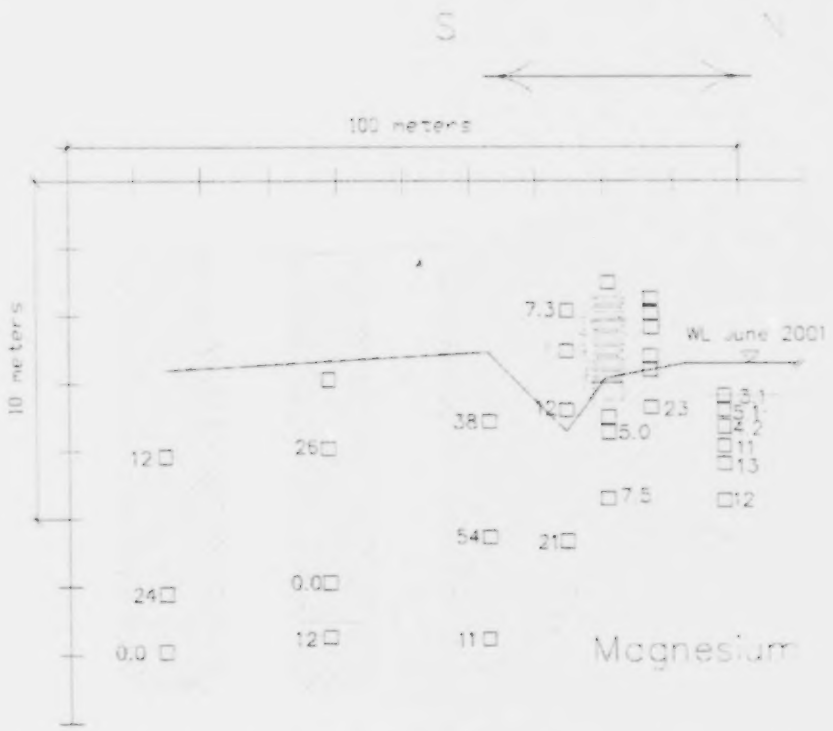

Figure 126. Site C, cell no. 2 magnesium concentrations (meq/L) from June 2001.

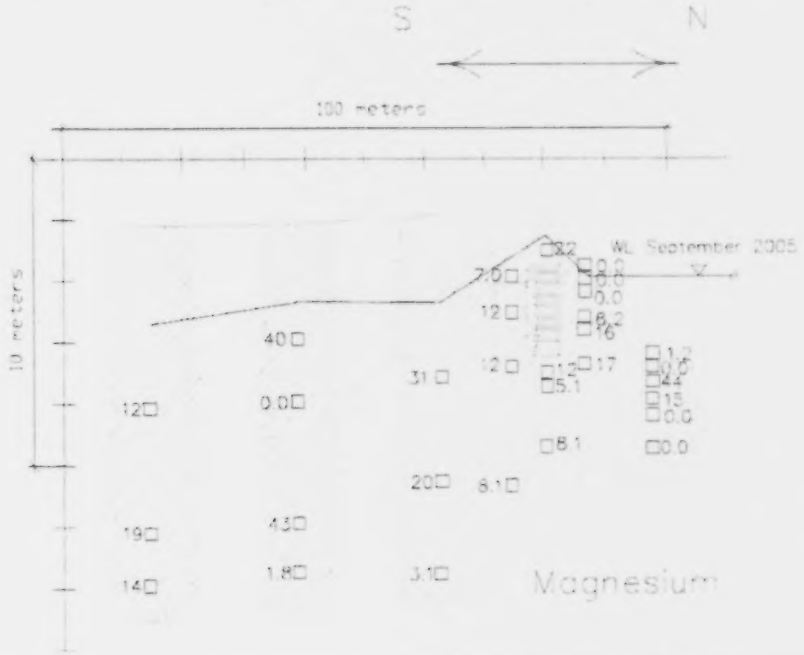

Figure 127. Site C, cell no. 2 magnesium concentrations (meq/L) from July 2005. *Indicates a value from 2004, as 2005 data was not available. ** Indicates a value from 2003, as 2004 data was not available.

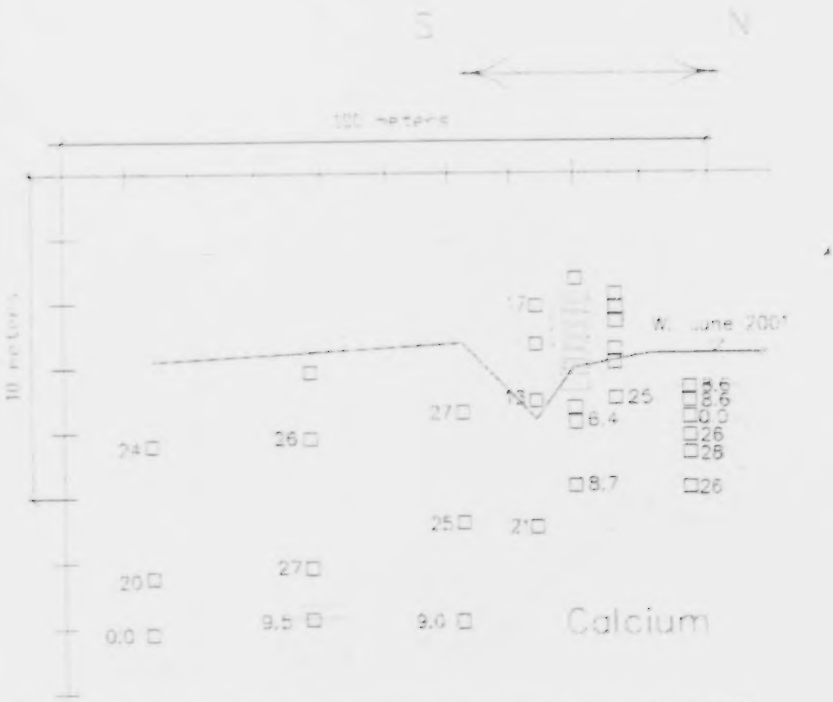

Figure 128. Site C. cell no. 2 calcium concentrations (meq/L) from June 2001.

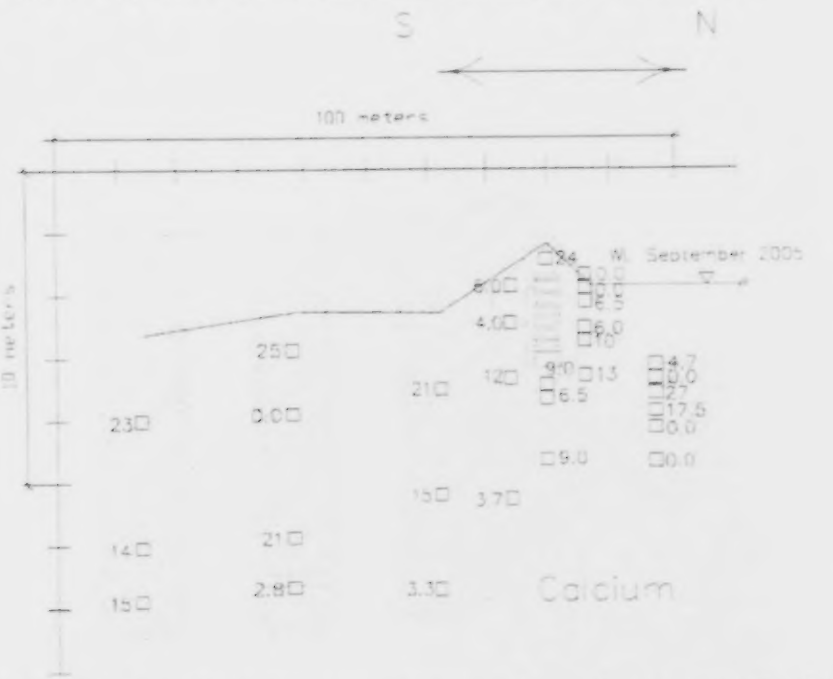

Figure 129. Site C. cell no. 2 calcium concentrations (mS/cm) from July 2005. *Indicates a value from 2004, as 2005 data was not available. ** Indicates a value from 2003, as 2004 data was not available.

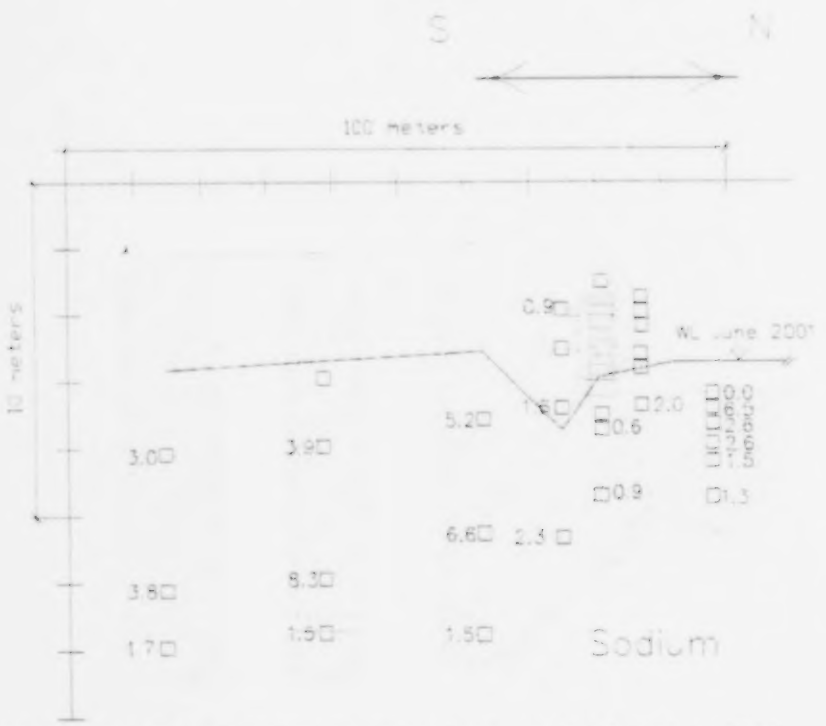

Figure 130. Site C, cell no. 2 sodium concentrations (meq/L) from June 2001.

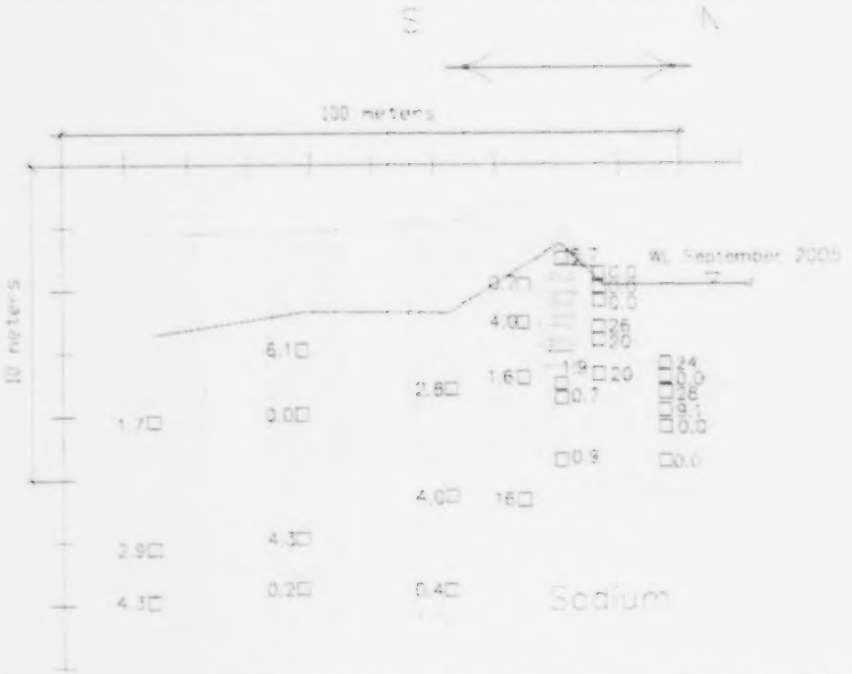

Figure 131. Site C, cell no. 2 sodium concentrations (meq/L) from July 2005. *Indicates a value from 2004, as 2005 data was not available. ** Indicates a value from 2003, as 2004 data was not available.

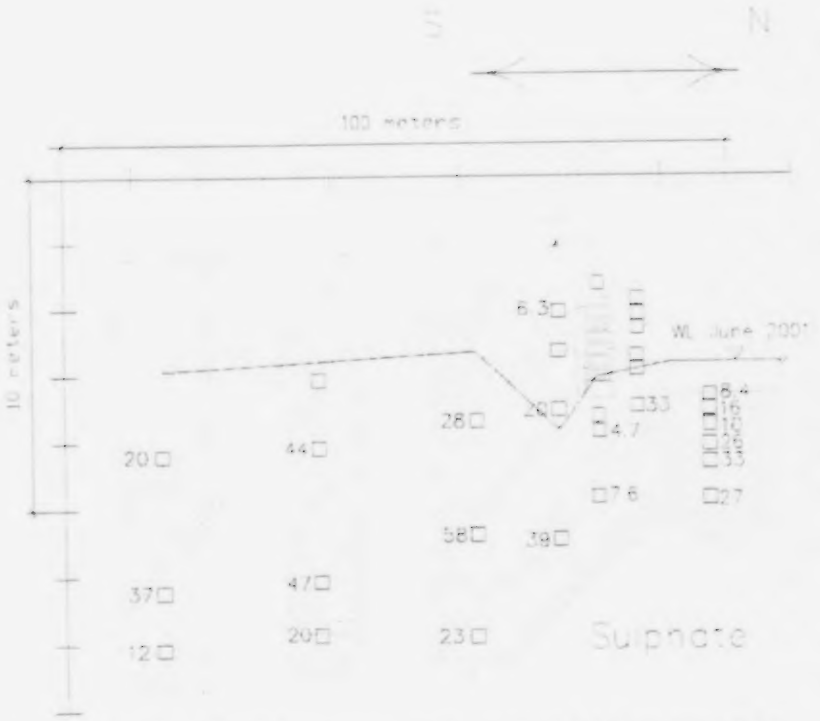

Figure 132. Site C, cell no. 2 sulphate concentrations (meq/L) from June 2001.

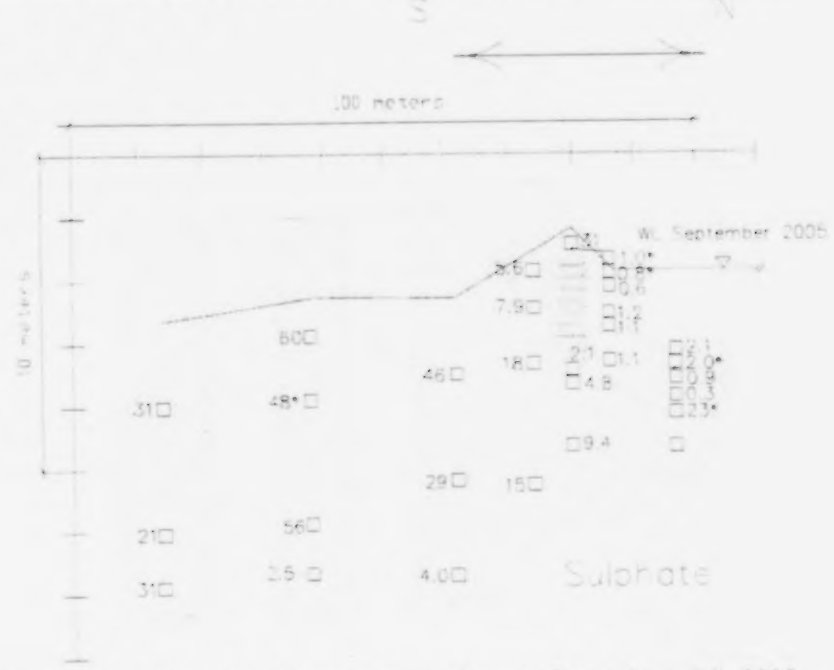

Figure 133. Site C, cell no. 2 sulphate concentrations (mS/cm) from July 2005.
*Indicates a value from 2004, as 2005 data was not available. ** Indicates a value from 2003, as 2004 data was not available.

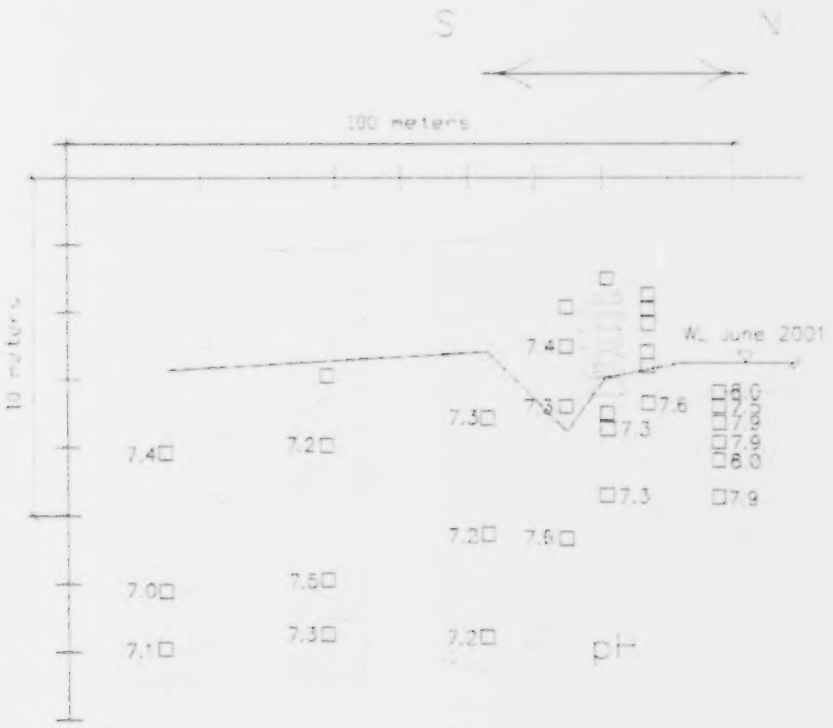

Figure 134. Site C. cell no. 2 pH readings from June 2001.

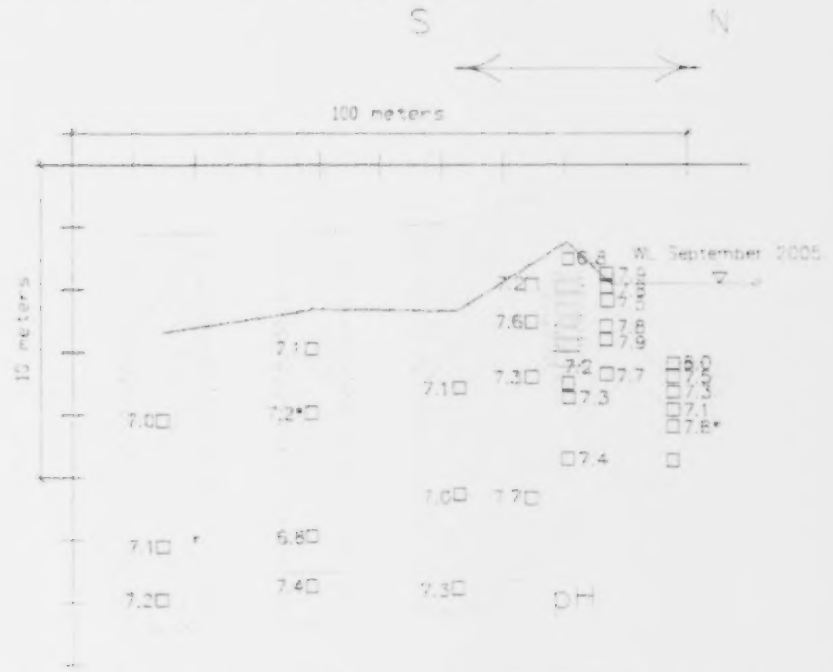

Figure 135. Site C. cell no. 2 pH readings from July 2005. *Indicates a value from 2004. as 2005 data was not available. ** Indicates a value from 2003. as 2004 data was not available.

CONCLUSION

Groundwater mounds have developed in the vicinity of all three EMS constructed in clay and/or clay till material. The maximum mound elevation appears to reflect the high water level of the storage. The mounds did not appear to dissipate when the storage was emptied causing groundwater discharge heads in Cell No. 2 of the storage for several months of the year.

The groundwater monitoring system installed at the three EMS sites has been successful in determining the extent of groundwater contamination due to EMS effluent seepage. Seepage has resulted in elevated ion levels (greater than10 meq/L) at depths up to 1.5 m below some of the storage cell and to distances up to 10 m directly out from the toe of the inside slop of the EMS since their commissioning between 1998 and 1999. Details of the extent of seepage at each site is given below.

Site A

Cell No. 1 at Site A has elevated ion levels to depths of over 3 metres and approximately 23 to 25 m south of the toe of the inside slope of the storage. These elevated ion levels are due to EMS effluent seepage near the storage and ion exchange and mineral dissolution at distances greater than five metres. High levels of magnesium, sulphate, and sodium are a result of mineral dissolution and ion exchange with ammonium and potassium. Calcium appears to have precipitated out of solution as calcium carbonate.

Cell No. 2 at Site A has experienced transport to depths greater than three metres below the storage and distances up to 10 metres adjacent to the side of the storage indicated by elevated concentrations (greater than 10meq/L) of chloride, ammonium, potassium, sodium, magnesium, calcium, and EC. Cell No. 2 was empty for one season prior to use and the liner may have been allowed to dry and crack allowing EMS effluent seepage from the storage.

Site B

Cell No. 1 at Site B has elevated ion concentrations (greater than 10 meq/L) approximately 3 m below the storage and three to six metres west of the side slope. This is indicated by chloride, alkalinity, ammonium, potassium and sodium concentrations as well as sulphate reduction in the same area. This seepage may be the result of liner damage during agitation and emptying of the storage.

Cell No. 2 at Site B has experienced minimum seepage beneath the storage (less than 1 m) and west of the side slope (less than 3 m) indicated by ammonium and potassium concentrations. Areas with elevated chloride correspond with areas of elevated sodium concentrations and areas of elevated alkalinity appear to correlate with areas of elevated calcium. This may indicate that chloride and alkalinity are being affected by sodium chloride and calcite concentrations within the parent material or ammonium and potassium are significantly attenuated compared to these anions.

Site C

Cell No. 1 at Site C has elevated ion concentrations to depths of 0.3 to 0.5 m and approximately 6 m west of the inside slope. This is indicated by elevated concentrations of chloride, ammonium, potassium and areas of sulphate reduction. Elevated areas of alkalinity, sulphate and magnesium may be the result of gypsum dissolution and release of magnesium from exchange sites.

Cell No. 2 at Site C has elevated ion concentrations (greater than 10 meq/L) to depths of three metres below the cell and three to eight metres adjacent to the toe of the inside slope indicated by elevated concentrations of chloride, sodium, EC and sulphate reduction. Potassium and ammonium are attenuated with respect to chloride with elevated concentrations indicated at depths of 0.3 to 0.5 m below the storage.

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Characterization and Propagation of a Hog Manure Seepage Plume in a Sandy Saskatchewan Soil

Paper No. 4

ADF Project # 20000265

Report Submitted to:
Agricultural Development Fund
Saskatchewan Agriculture and Food

Prepared by:

T. A. Fonstad, Ph.D., P.Eng. and Crystal Rinas, B.E.
Department of Agricultural and Bioresource Engineering
University of Saskatchewan

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ABSTRACT

A groundwater monitoring system was installed at an existing earthen manure (EMS) site in Saskatchewan. The site is located in a sandy soil and the EMS was constructed without a low permeability clay liner in 1984. This site represents a scenario for potential EMS leachate seepage. A contaminate plume, indicated by elevated chloride concentrations, extends approximately 60 m south of the storage and approximately 6 m vertically downwards. Multispecies transport has resulted in a hardness halo in advance of the plume and attenuation of ammonium and potassium.

INTRODUCTION

Earthen manure storages are a potential source of groundwater contamination. Elevated levels of nitrate-nitrogen in groundwater are a known threat to both human and animal health, therefore; concerns regarding potential groundwater contamination as a result of seepage from EMS have been the primary motivator for monitoring.

This site was instrumented as part of a project set up to monitor EMS and provide data regarding the long term performance and safety of earthen hog manure storages. To reach this objective, it was necessary to monitor newly constructed storages, but also to complete detailed investigations of an existing older storage. The data collected from this project should increase public assurance and investor confidence in the hog industry. Results will also confirm the role of liners in new storages, the site characteristics required for establishment of new storages and possible requirements for decommissioning.

This paper will look at the results of groundwater data collected from seepage monitoring systems at an existing EMS established in 1989 in a sandy soil. Monitoring system components were installed in the winter of 1999. Groundwater chemical data was collected annually from 2001 to 2005.

BACKGROUND

EMS Seepage Monitoring

Numerous research studies have been conducted to study the seepage of contaminants from EMS into the surrounding groundwater. The driving force behind these studies is the potential health effects nitrogen contamination can have on human/animal health. Fonstad (2004) summarizes the chemistry of liquid swine manure and lists ammonium nitrogen as one of the most abundant ions in EMS effluent.

Studies have shown that when EMS are constructed improperly without a low permability liner, or when the liner has been eroded or cracked, a contaminant plume develops beneath the storage (Ham and DeSutter 2000; McMillan and Woodbury 2000; Westerman et al. 1995; Cirvalo et al. 1979; Ritter and Chirnside 1990). The extent of the contaminant plume varies with age, soil type, and water table depth with the worst type

scenario being an EMS constructed without a liner on a sandy soil with a high water table.

Plumes from EMS in the Canadian Prairies do not appear to have nitrogen present as nitrate, possibly due to lower groundwater temperatures (6° C) and low dissolved oxygen levels inhibiting microbial conversion (Fonstad 2004).

The measurement of groundwater chemistry is a method commonly used to monitor EMS seepage (Parker et al. 1999). The extent of seepage determined through installation of shallow monitoring wells has been undertaken in various locations in the United States of America and Canada. Westerman et al. (1993) reported nitrogen within an EMS present as ammonium. Effluent samples from the plume surrounding the same EMS indicated as much as 50% of the nitrogen was present as nitrate: this prevalence is expected as ground waters of the surficial sands in the North Carolina site have warm temperatures (near 20°C) and contain high levels of dissolved oxygen, both of which promote microbial conversion of ammonium to nitrate. Ciravolo et al. (1979) recorded ammonium and nitrate near an EMS and nitrification near the front of the plume at both locations they studied. These results may be due to warm temperatures and high dissolved oxygen levels in the shallow groundwaters of the Mid-Eastern United States where the study took place.

Other methods to determine EMS seepage include the soil samples, electromagnetic surveys, and oxidation/reduction zoning. The pros and cons of all methods are evaluated in Fonstad (2000).

Geochemical Conditions within an EMS Effluent Plume

Once a leachate leaves an EMS its geochemistry will be altered. The most active processes are dilution, adsorption, exchange reactions and precipitation (Islam et al. 2001). Any biochemical processes are likely to take place under anaerobic conditions (Islam et al. 2001) unless the EMS is located in shallow groundwaters in a warm climate. In order to understand the mechanisms controlling the species of concern within an EMS effluent plume, the following background information on nitrogen transport, redox conditions and cation exchange is provided.

Nitrogen transport Nitrogen is subject to many possible transformations as it is leached through the soil. These transformations depend on conditions at the site. It could be adsorbed into the soil matrix, oxidized or reduced, or even assimilated into the soil biomass.

Nitrogen can occur in different oxidation states from −3 (NH_3 and NH_4^+) to +5 (NO_3^-). Many of the transformations between states are carried out by microorganisms at normal temperatures and pressures (Paul and Clark, 1996). For example, nitrogen is present in anaerobic waste storages, on exchange sites in the clay lattice, and in many fertilizers in the ammonia (NH_3) or ammonium (NH_4^+ or N(-3)) state while nitrate (N(5)) is present in the aerobic zone of surface soils and in some fertilizers.

The positive charge on the ammonium ion leads to ammonium adsorption to clays and organic matter. NH_4^+ is held on the exchange complex where it can be replaced by cations from the soil solution.

NH_4^+ can be oxidized to NO_3^- by chemoautotropic bacteria if oxygen levels are sufficient. This process in known as nitrification and is shown below:

$$\underset{-3}{NH_4^+} \longrightarrow \underset{-1}{NH_2OH} \longrightarrow \underset{+1}{NOH} \longrightarrow \underset{+3}{NO_2^-} \longrightarrow \underset{+5}{NO_3^-}$$

Once ammonium is converted to nitrate, the nitrogen has a negative charge and becomes an unattenuated ion and cannot be adsorbed on to negative soil exchange sites.

Redox conditions The issues of concern when storing animal manure in EMS are large quantities of organic matter and relatively high concentrations of nitrogen. Any plume which develops will likely experience reducing conditions and ion exchange; both factors are significant in regards to the transport of nitrogen in the effluent plume. If ammonium seeps from the EMS into a reducing environment, it will tend to stay as ammonium and be subject to ion exchange. This will lead to attenuation of nitrogen in the effluent plume and may provide for some protection against nitrogen contamination of nearby aquifers. An understanding of redox zoning and adsorption processes will aid in the interpretation of investigations of transport mechanisms of EMS effluent.

Cation exchange Ion exchange has an effect on plume development and geochemistry. In the case of EMS leachate plumes there are often many contaminant species involved When several species are present, complex breakthrough patterns can occur as the plume progresses (Vulava et al. 2002; Voegelin et al. 2000). These complex breakthrough patterns occur due to the competitive adsorption of cations. Certain cations are preferred on the soil exchange sites. This preference is based on (Fonstad 2004):

- the charge of the ions;
- the size of the ion or hydrated radius;
- the properties of the exchanger (e.g. clay mineral);
- quantity and ratios of the various valence of ions present; and
- the total solution concentration.

The cations that are adsorbed by the soil do not appear in the contaminant plume as rapidly as unreactive anions such as chloride. This presents a separation of the ions as they appear in the plume known as a chromatographic sequence.

SITE CHARACTERIZATION

Site No. 1 was constructed in 1984 to service a 250-sow farrow to finish operation which produces approximately 7300 m^3 of effluent per year. The site was constructed in a lacustrine deposit: soils consist of approximately 6 to 8 m of sands with lenses of silts and clays over lying at least 4 to 6 m (maximum depth of investigation) of firm clay with lenses of sands and silts.

The EMS at this site was constructed without a liner in the same fashion as construction of an earth borrow pit. Excavation equipment accessed the excavation from the ends during construction resulting in relatively steep side slopes (2:1) and gradual end slopes (4:1 to 5:1). Material from the excavation was used to construct the berms on the north, east and south sides. The top of the berm at the west end of the EMS is at original ground elevation. The storage was excavated until a clay layer was encountered at approximately 2-2.5 m below grade. No effort was made to compact the soils additional to the weight of the construction equipment during excavation.

The groundwater gradient at this site was determined to be almost perpendicular to the EMS sides and flow from north to south. The relatively steep side slopes perpendicular to the groundwater gradient and the granular upper soils with the underlying clay soils resulted in the development of a seepage plume believed to extend at least 30 m from the storage as indicated by a preliminary investigation in 1994. Due to the extent of this plume the EMS was chosen for further investigation.

Site Background

Test drilling at the site indicates 100 to 300 mm of top soil followed by silts and sands to a depth of 5 to 7 meters. This was followed by layered soft sands, silts and clays overlaying stiff clay at depths of 5 to 10 meters below grade.

Water table elevations range from 1.5 to 3 m below ground surface. This site represents a poor location for an EMS due to the sandy soils and high water table.

Monitoring System Installation

On February 15 to 19, 1999, the Geotechnical Division of the Prairie Farm Rehabilitation Administration (PFRA) of Agriculture and Agri-food Canada and the Department of Agricultural and Bioresource Engineering at the University of Saskatchewan installed monitor wells and obtained soil samples adjacent to the EMS. Piezometer nests were installed in a line running south from the EMS, which was determined to be the general direction of groundwater flow by previous studies (Fonstad and Maule, 1995). Soil cores were extruded in PFRA's lab in Regina on March 8 to 10, 1999 and samples were sent to the University of Saskatchewan Soil Science Laboratory for chemical analysis. The remaining soil was analyzed by PFRA for grain size, Atterberg Limits, density, specific gravity, water content and hydraulic conductivity.

On March 22, 1999, drilling was completed through the ice in the EMS. Drilling was accomplished with a rotary drill rig using a hollow stem auger and Shelby tubes for sampling. The rig was parked on the ice surface of the EMS and the hollow stem auger drilled down to the soil surface. Shelby tube samples were taken and the auger drilled down to the level of the sample. This procedure was repeated to a depth of 3 to 4 m. Samples were placed in cold storage until extrusion was possible. The finished test hole was then cleaned out and an instrument bundle was placed on the bottom. The bundle was sand packed and then sealed with bentonite up to the level of the next bundle installation. Three bundles were placed in the hole: at the bottom, midpoint, and just below the soil surface. Instrument bundles consisted of a thermocouple, redox probe, pneumatic piezometer and two 3.2 mm diameter tubes (Figure 1). The bundle was placed inside of 300 mm of 50mm diameter slotted screen. 25mm poly tubing was placed over the cables and attached to the screen with a watertight seal. After bundle installation, the tubing was run to the EMS bank for installation in a weatherproof panel. These installations allow measurement of temperature, ORP and hydraulic head below the EMS as well as provide the ability to obtain a water sample at the elevation of the installed bundle.

In June 2005, the University of Waterloo, in conjunction with the University of Saskatchewan, installed multilevel piezometers in several locations (C44 to C50) at the site. These locations are shown on the site plan (Figure 2). An electromagnetic survey of the site was conducted to determine the need for more piezometers where the plume was not previously monitored.

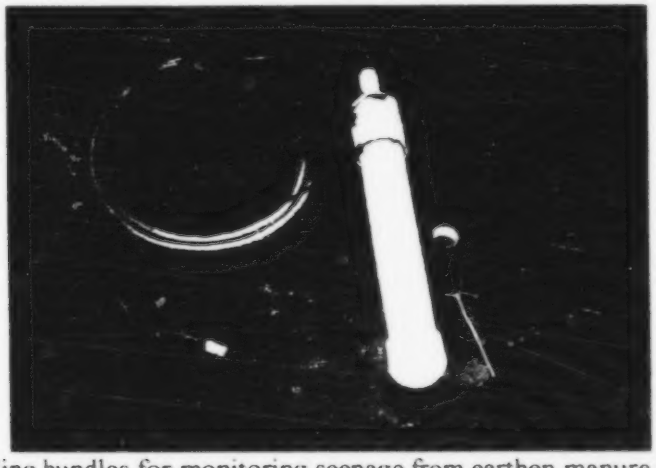

Figure 1. Sampling bundles for monitoring seepage from earthen manure storages

Gas samplers were installed on October 4, 2000. Stacked samplers were installed at five different locations. Sampling depths are 0.1, 0.3, 0.5, 1.0 and 2.0 meters below ground surface.

The location of all sampling points with respect to the EMS are shown in Figure 2.

Figure 2. Instrument locations at Site No. 1 (all distances in metres).

METHODS AND ANALYSIS

Water Sampling

Water sampling at the site was accomplished by bailing each piezometer with a plastic 1 L bailing tube until approximately three piezometer volumes had been removed or the piezometer was empty. Piezometers were then allowed to recover for 1 to 3 hours. A water sample was then retrieved using the tube, and placed in a 100 mL sterile plastic container and stored in a cooler for transport. A portion of each sample were passed through a 0.45 µm filter and analyzed in the field for pH and electrical conductivity (EC) by electrode and alkalinity by titration. Samples from 2001 to 2003 were then taken to the laboratory at the Department of Geological Sciences at the University of Saskatchewan where they were diluted and decanted into vials and then analyzed for Na, Ca, Mg, NH_4, K, Cl, NO_3, and SO_4 using a Dionex Ion Chromatograph.

In 2004 and 2005, samples were filtered to 0.45 µm and analyzed for EC, pH, temperature and alkalinity in the field. Filtered water samples from each piezometer were

sent to the Saskatchewan Research Council for analysis of major ions and minor ions. Special care was taken to ensure minimal air was introduced to the sample; samples were kept at temperatures between 1 °C to 5 °C and samples were delivered to the laboratory for analysis within several hours of retrieval. Major ions (Ca, Mg, Na, K and SO_4^{2-}) were analyzed by ICP-IRS, carbonates (HCO_3-, CO_3 and alkalinity) by acid titration, ammonium and chloride by colorimetric analysis, and sulphide and pH by electrode.

Water samples were retrieved from piezometers C15, C18, C21, C24 and C29 in February 2000 and from C8 through C10, C14 through C24 and C27 through C29 in May 2004. These samples were sent to the Saskatchewan Research Council for analysis of metals and organic carbon, in addition to major ions. Organic carbon was analyzed by Dohrman Pheonix carbon analyzer and metals by ICP-AES.

Piezometric Head

Pneumatic piezometers below the EMS were read with an RSI Digital Pneumatic Piezometer Reader using Argon gas to pressurize the piezometer. Pressure readings were recorded in both kilopascals and pounds, and then converted to a height of water using calibration curves supplied by the manufacturer. Standpipe piezometers were read by dropping a standard water level tape meter down each piezometer and recording the level at which the signal is activated.

RESULTS AND DISCUSSION

Figures 1 to 19 show geologic sections of the site with concentration profiles for electrical conductivity, chloride, ammonium, alkalinity, potassium, magnesium, calcium, sodium, sulphate and pH in May 2001 and May 2005.

In 2005, a chloride plume is evident at 50 m to 60 m from the EMS, while ammonium and potassium are attenuated to a distance of less than 30 m. Magnesium concentrations peak at ~20 m and again at 43 m from the EMS; concentrations at these locations are 150 and 100 times EMS effluent concentrations and 15 and 10 times background groundwater concentrations, respectively. These magnesium concentrations are likely the result of ion exchange absorbing potassium and ammonium and releasing magnesium. Calcium concentrations peak at ~43 m from the EMS, at 4 times the EMS effluent concentration and 6 times the background groundwater concentration. These calcium concentrations are likely a result of ion exchange where calcium is released and magnesium absorbed, due to the high magnesium levels discussed earlier.

The 2005 profiles indicate a plume extending approximately 50 m to 60 m south of the EMS and extending vertically down to approximately 6 m below the EMS. The vertical transport is indicated by elevated concentrations of chloride, alkalinity, magnesium and calcium in the partially confined sand layer at approximately six to seven m below grade. Potassium and ammonium appear confined to the upper unconfined sand layer and are attenuated compared to the chloride plume. Potassium experiences a relative constant attenuation and appears to be preferentially adsorbed over ammonium. Ammonium

attenuation appears limited to near the leading edge of the ammonium plume, possibly the result of high magnesium and calcium concentrations at this location limiting absorption of ammonium to soil exchange sites. A magnesium front is evident at approximately 20 m from the EMS. Magnesium and calcium produce a hard water front approximately 30 to 50 m from the EMS, and on the north side of the partially confined sand layer at 6 to 7 m below grade.

The cross sections, in Figures 5 and 6, indicate that since 2001, the concentrations of chloride have increased 25% vertically and 60% horizontally. The edge of the chloride plume in 2001 was at approximately 55 m from the EMS. The concentrations of chloride at this edge increased from 1 to 3 meq/L in 2001 to 3 to 10 meq/L in 2005. The current edge of the chloride plume is approximately 65 m from the EMS. This current edge has concentrations of chloride ranging from 1 to 5 meq/L compared the background chloride levels measured in 2001 of 0.5 to 2 meq/L.

Although the chloride plume has grown in the past four years, the edge of the ammonium plume has not. The concentrations of ammonium 25 m away from the EMS have increased approximately 25% or 5 to 8 meq/L since 2001, but the plume does not appear to have advanced further. Other profiles, sodium, magnesium, EC, potassium, calcium and alkalinity have not changed significantly and in some cases have been reduced from 2001 to 2005. This reduction may be due to an increase in groundwater flow (a dilution effect) in the past few years. Sulphate levels may have decreased due to a larger anaerobic area developing beneath the storage inducing sulphate reduction.

Table 1 gives the metals and organic carbon concentrations collected in 2001 and 2005. Changing redox conditions are an indication of plume advancement. At C24, a ten fold decrease in iron concentrations were found in solution.

Table 1. Water analysis results for piezometers located at Site No. 1

		2001					2005				
Well No.	Distance from source	Fe (mg/L)	Mn (mg/L)	Si (mg/L)	Sr (mg/L)	DOC (mg/L)	Fe (mg/L)	Mn (mg/L)	Si (mg/L)	Sr (mg/L)	DOC (mg/L)
C29	-20	0.79	0.38	3.50	0.55	4.7	0.55	0.36	6.00	0.48	5.6
Source	0	0.02	0.05	81.30	0.34	6300	0.02	0.05	81.30	0.34	6300
"B"	0	5.27	0.09	9.60	1.31	750					
C16	12	2.02	0.15	5.60	3.47	58					
C15	12	5.02	0.10	12.90	2.88	380	13.00	0.05	25.70	2.70	1200
C14	12	34.70	0.26	7.00	4.19	270					
C19	22	16.5	0.52	13.40	1.26	84					
C18	22	9.13	0.04	11.80	4.36	410	21.00	0.05	34.00	6.90	530
C17	22	2.20	0.72	9.40	0.90	8					
C20	33	81.9	1.67	14.90	2.78	100					
C21	33	67.4	0.23	13.60	3.13	300	94.00	0.54	28.00	2.80	250
C22	33	2.30	0.80	9.40	0.89	7					
C24	44	86.2	0.62	8.80	4.05	570	0.07	5.50	21.00	2.10	14
C8	51	0.01	0.63	5.00	1.41	10					
C27	60	4.78	1.60	10.2	0.73	6.4					
C28	60	3.50	0.59	7.50	1.45	9.8					
C9	68	4.36	0.71	8.40	0.78	7.9					

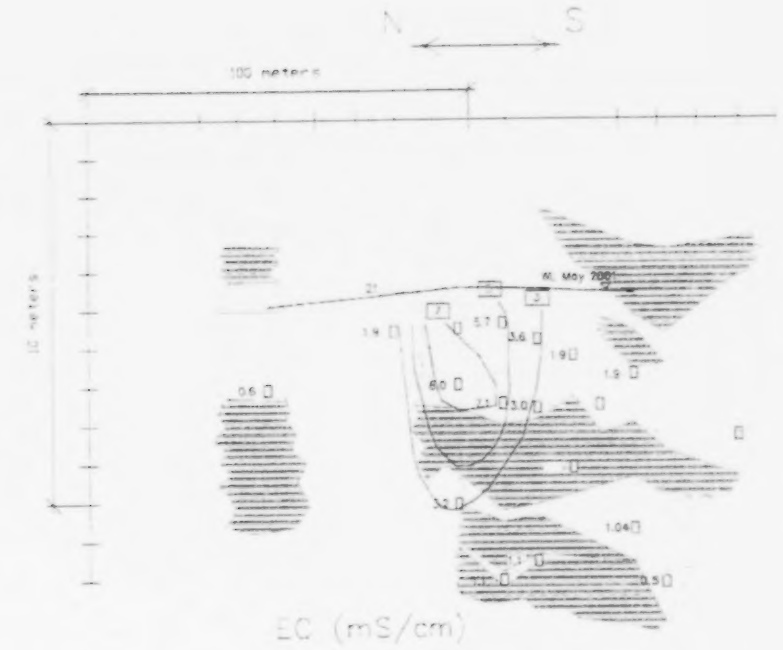

Figure 3. Site No. 1 electrical conductivity readings (mS/cm) from May 2001.

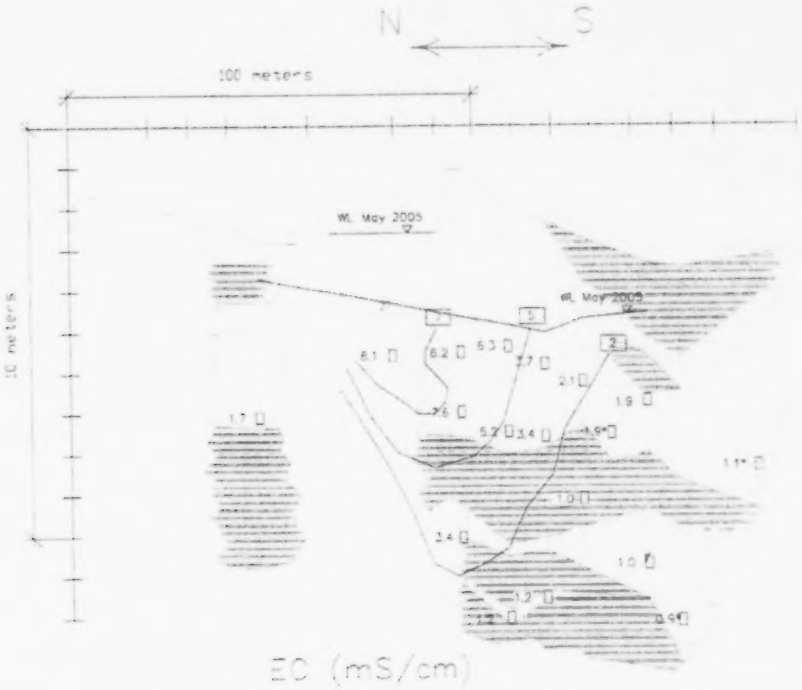

Figure 4. Site No. 1 electrical conductivity readins (mS/cm) from May 2005. *Indicates 2004 value, as 2005 data is not available.

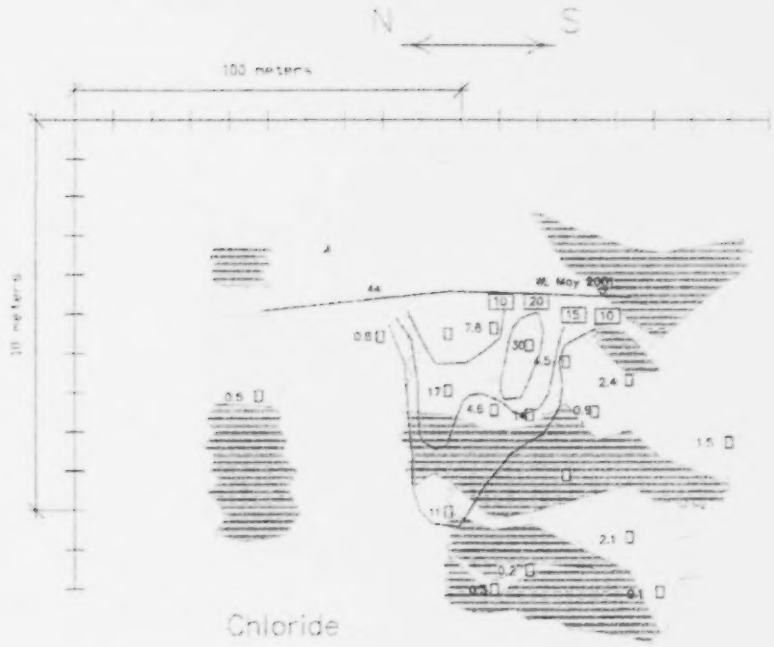

Figure 5. Site No. 1 chloride concentrations (meq/L) from May 2001.

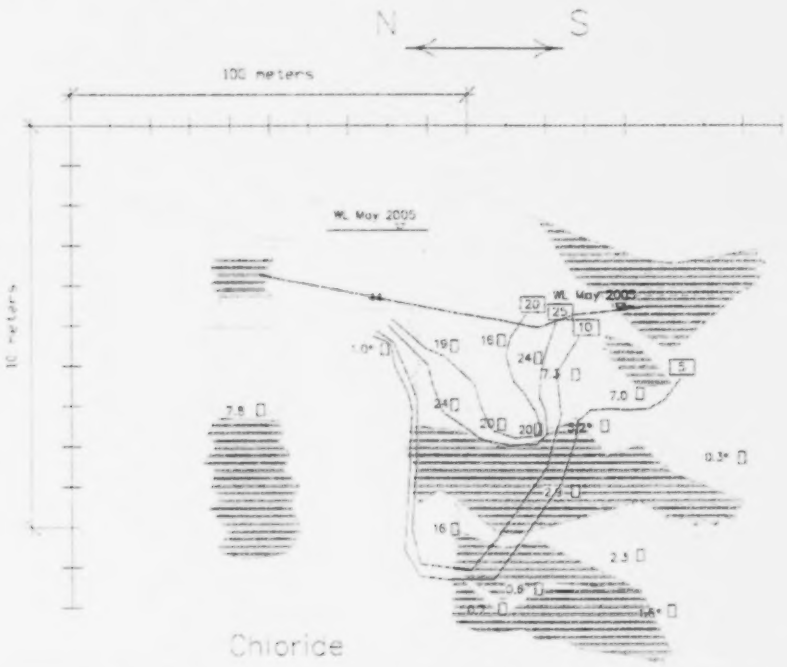

Figure 6. Site No. 1 chloride concentrations (meq/L) from May 2005. *Indicates 2004 value, as 2005 data is not available.

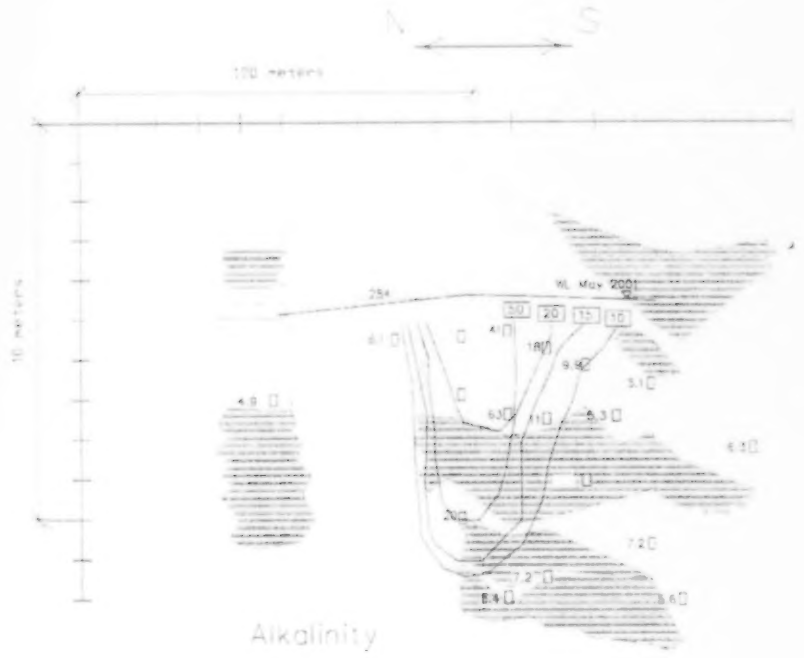

Figure 7. Site No. 1 alkalinity concentrations (meq/L $CaCO_3$) from May 2001.

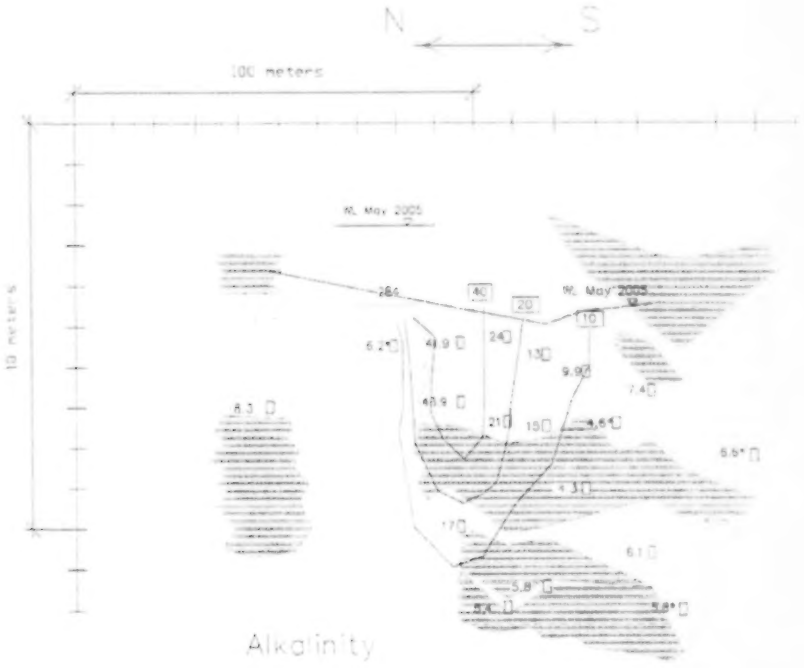

Figure 8. Site No. 1 alkalinity concentrations (meq/L $CaCO_3$) from May 2005.
*Indicates 2004 value, as 2005 data is not available.

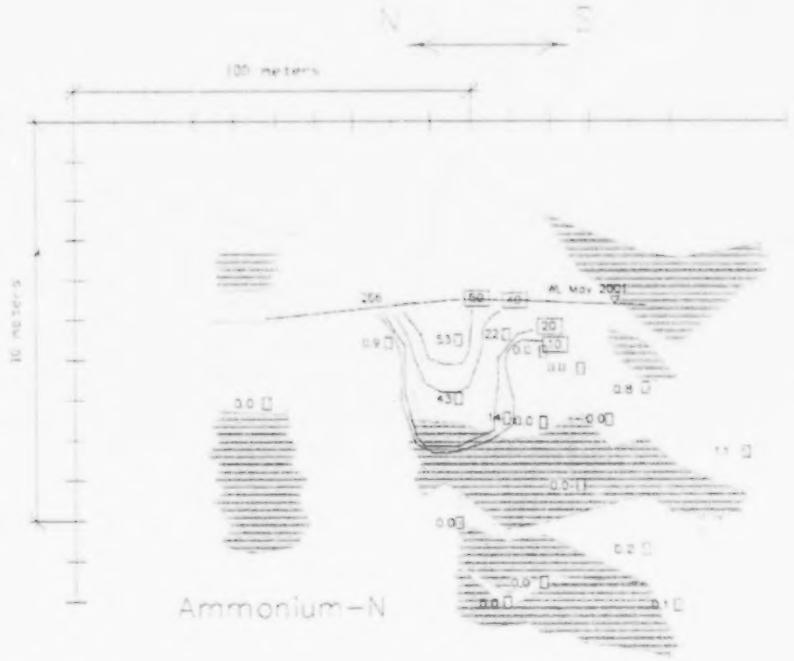

Figure 9. Site No. 1 ammonium concentrations (meq/L N) from May 2001.

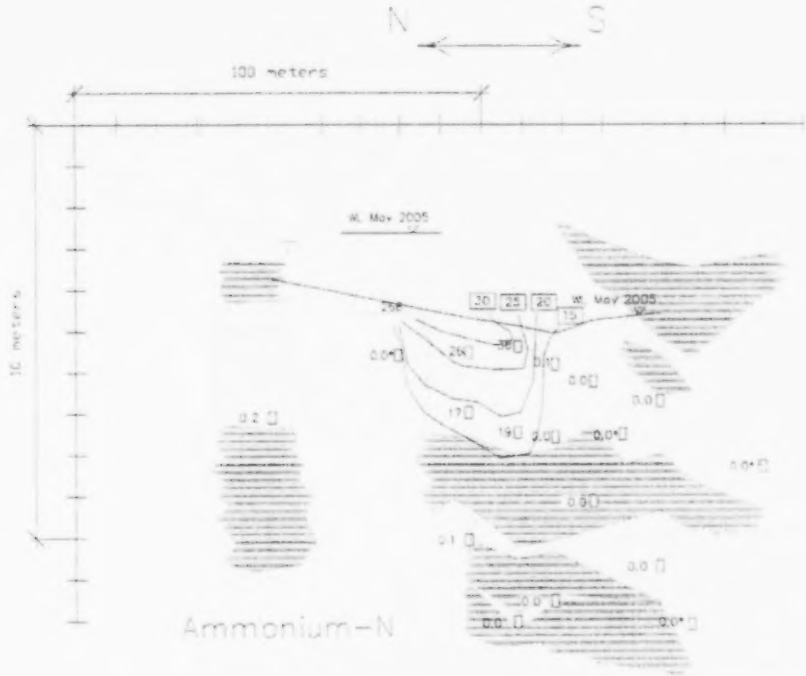

Figure 10. Site No. 1 ammonium concentrations (meq/L N) from May 2005. *Indicates 2004 value, as 2005 data is not available.

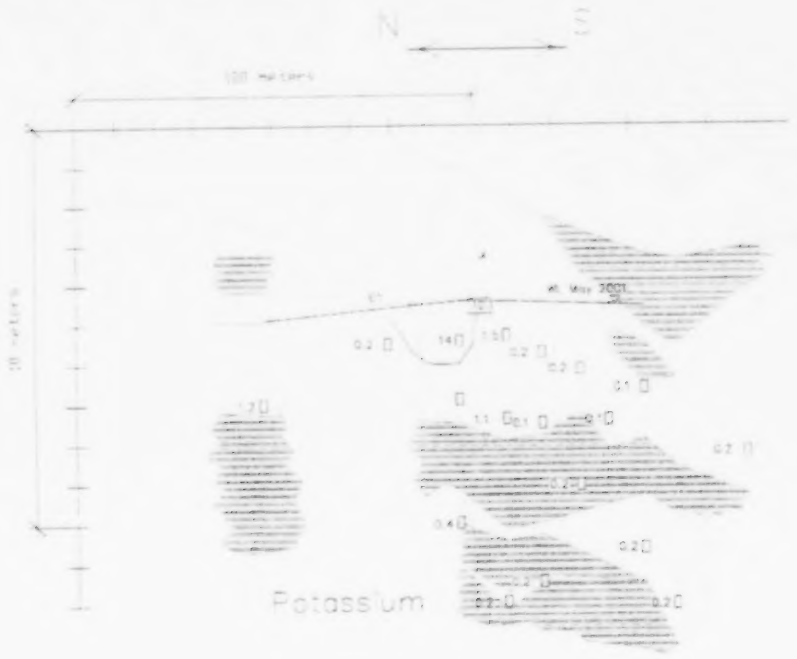

Figure 11. Site No. 1 potassium concentrations (meq/L) from May 2001.

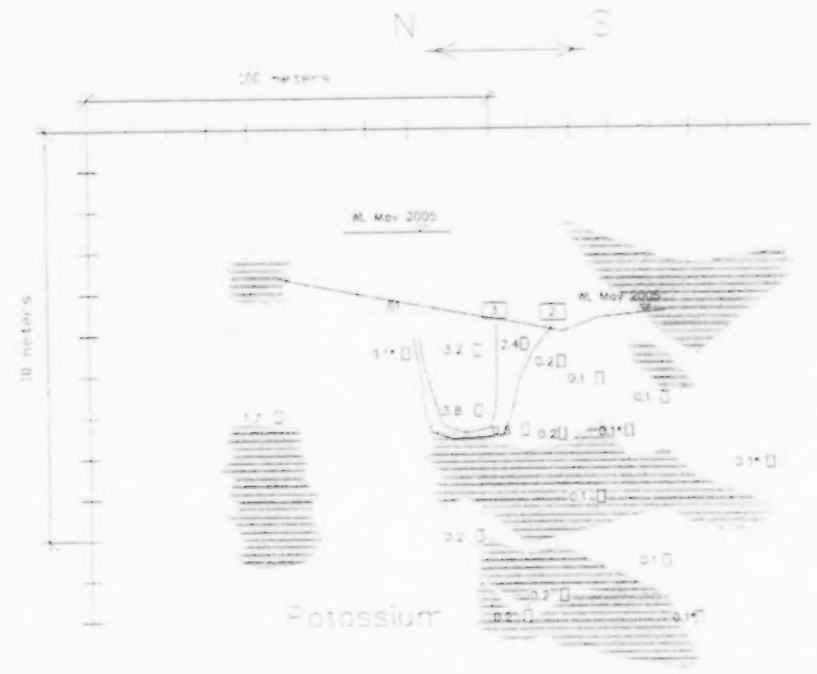

Figure 12. Site No. 1 potassium concentrations (meq/L) from May 2005. *Indicates 2004 value, as 2005 data is not available.

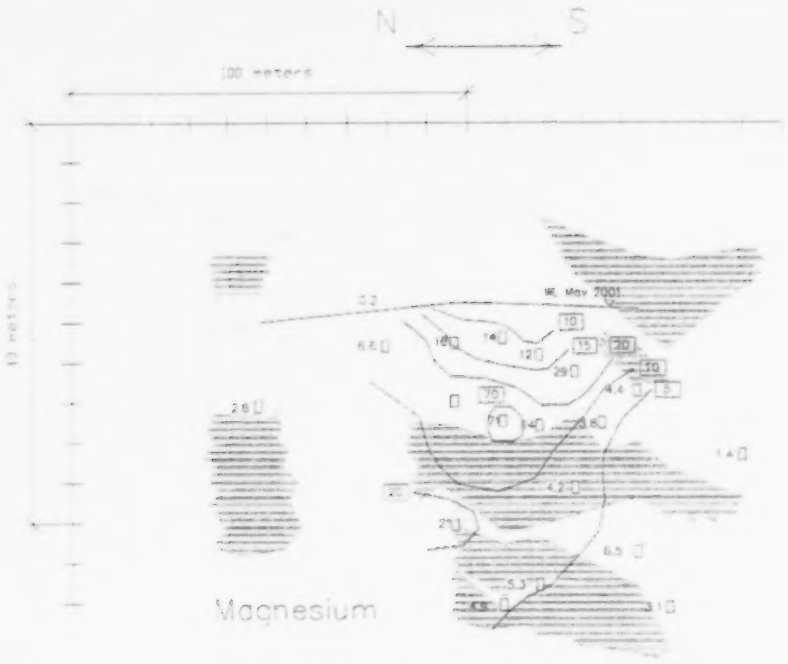

Figure 13. Site No. 1 magnesium concentrations (meq/L) from May 2001.

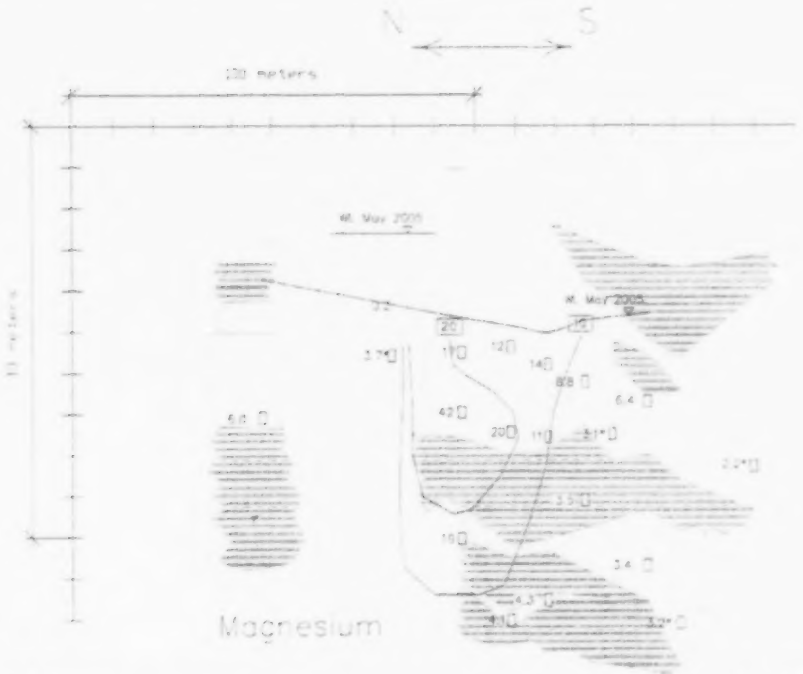

Figure 14. Site No. 1 magnesium concentrations (meq/L) from May 2005. *Indicates 2004 value, as 2005 data is not available.

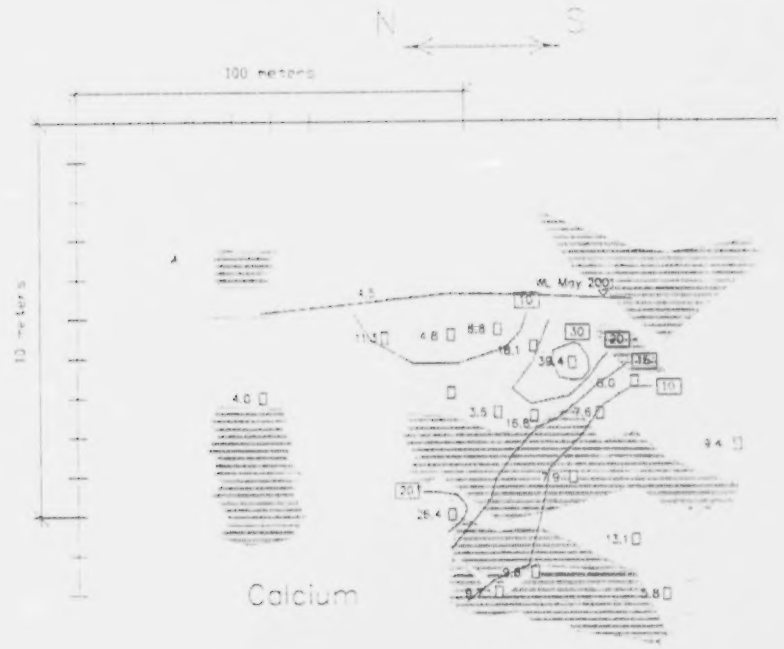

Figure 15. Site No. 1 calcium concentrations (meq/L) from May 2001.

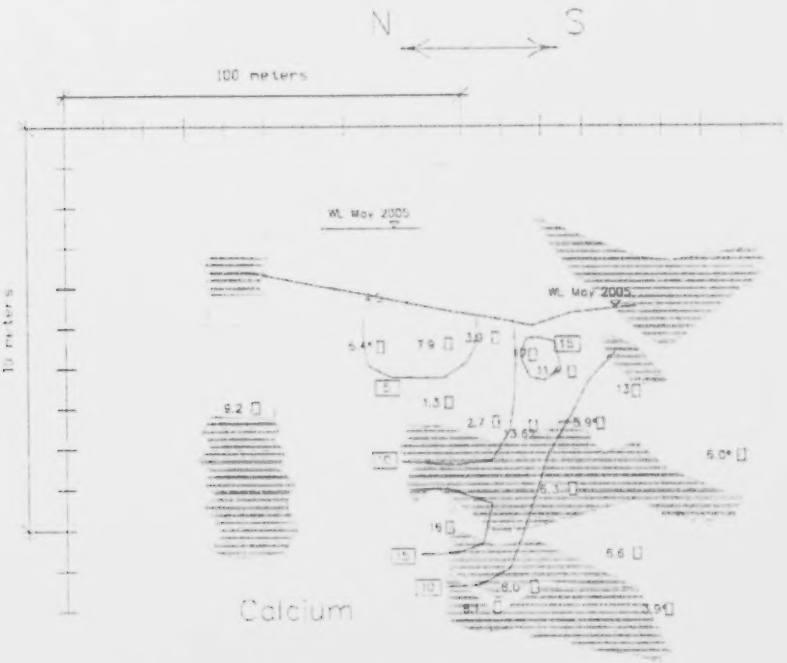

Figure 16. Site No. 1 calcium concentrations (meq/L) from May 2005. *Indicates 2004 value, as 2005 data is not available.

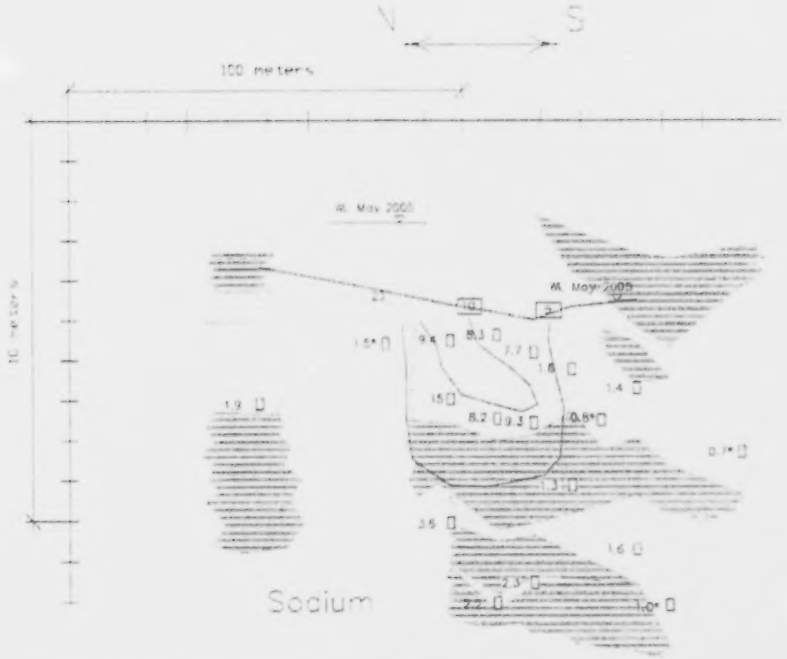

Figure 17. Site No. 1 sodium concentrations (meq/L) from May 2001.

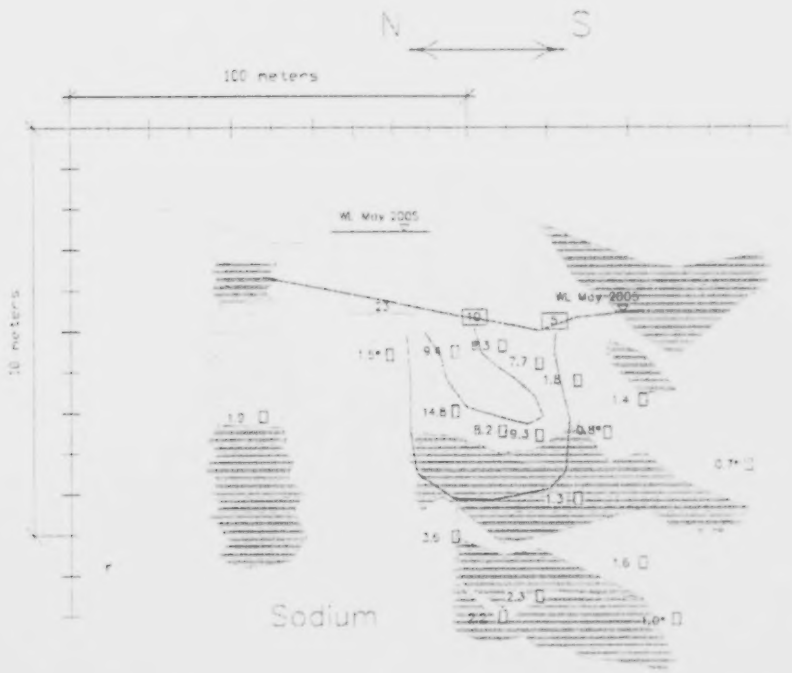

Figure 18. Site No. 1 sodium concentrations (meq/L) from May 2005. *Indicates 2004 value, as 2005 data is not available.

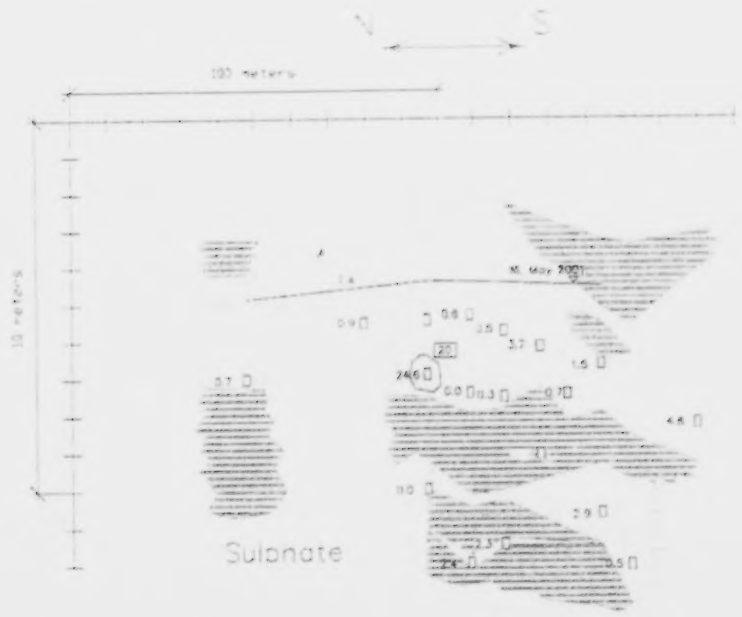

Figure 19. Site No. 1 sulphate concentrations (meq/L) from May 2001.

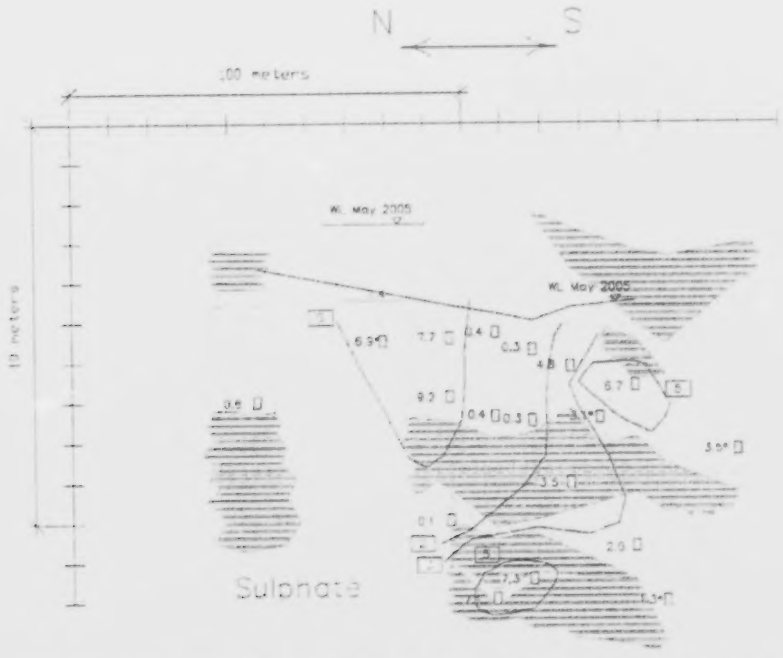

Figure 20. Site No. 1 sulphate concentrations (meq/L) from May 2005. *Indicates 2004 value, as 2005 data is not available.

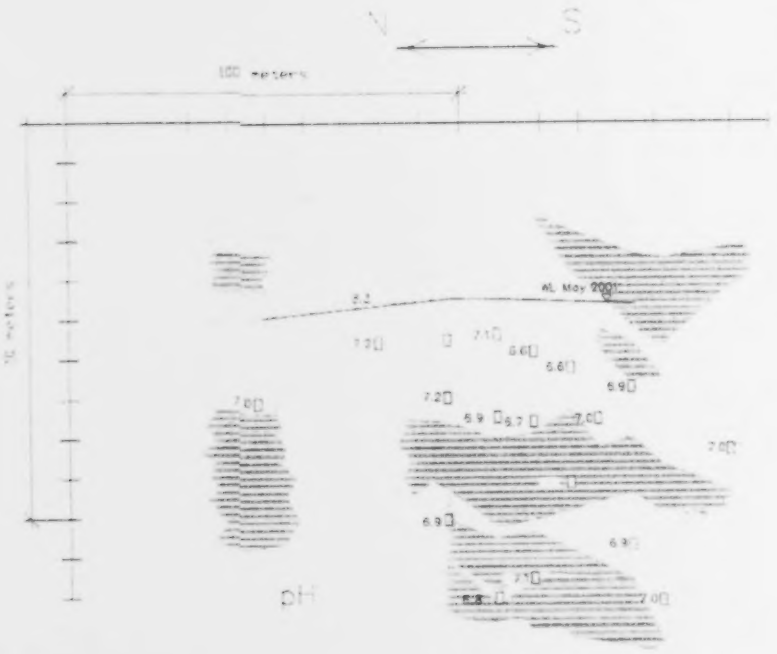

Figure 21. Site No. 1 pH readings from May 2001.

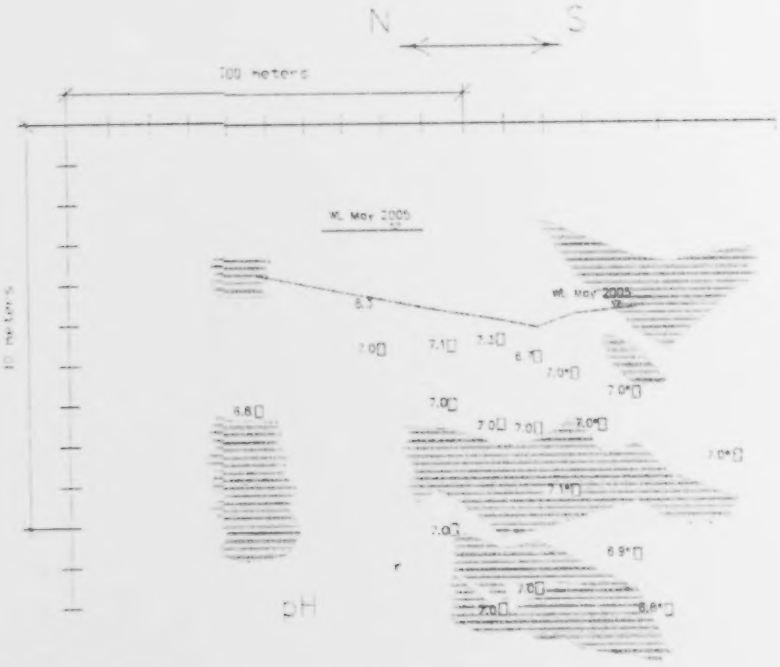

Figure 22. Site No. 1 pH readings from May 2005. *Indicates 2004 value, as 2005 data is not available.

CONCLUSION

Multispecies transport through the sandy material at this site has resulted in plume consisting of a hardness halo in advance of the plume and attenuation of ammonium and potassium. Ion exchange as a result of ammonium and potassium in the EMS effluent has caused release of magnesium and calcium into solution. Magnesium release is much greater than calcium suggesting magnesium release occurs first. Ammonium and potassium transport are retarded by factors of approximately 2 and 4 respectively. This relatively low attenuation of ammonium should be of concern when evaluating EMS sites.

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Appendix A – Project Photos

Photo 1 - Horizontal installation of groundwater monitoring bundles benearth EMS.

Photo 2 - Automated system for ORP and temperature readings.

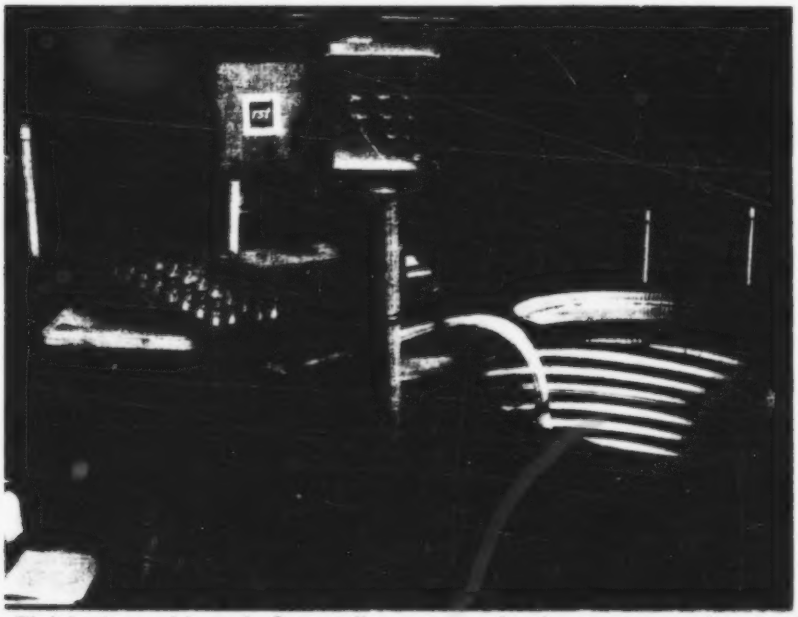

Photo 3 - Finished panel boards for reading pneumatic piezometers and retrieving water samples.

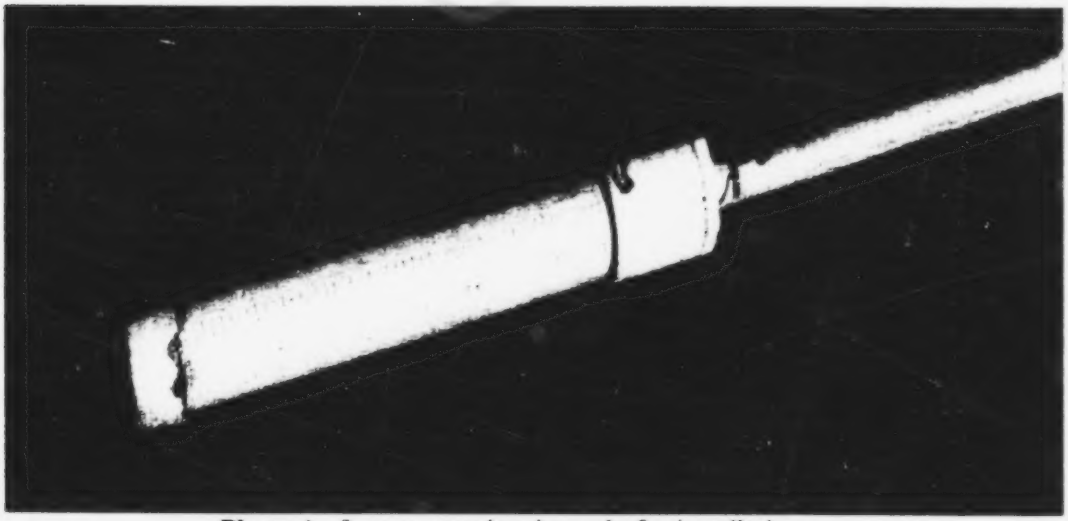

Photo 4 – Instrumentation tip ready for installation.

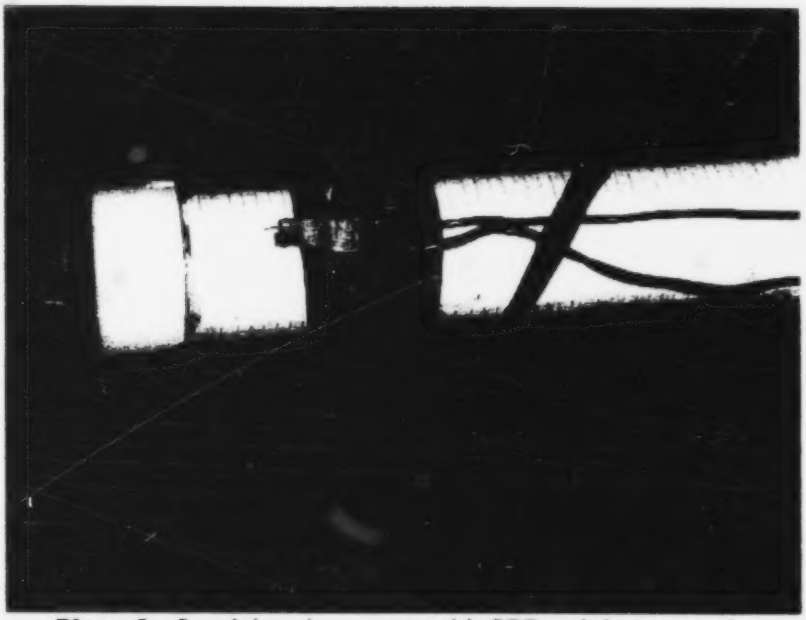

Photo 5 – Standpipe piezometer with ORP and thermocouple.

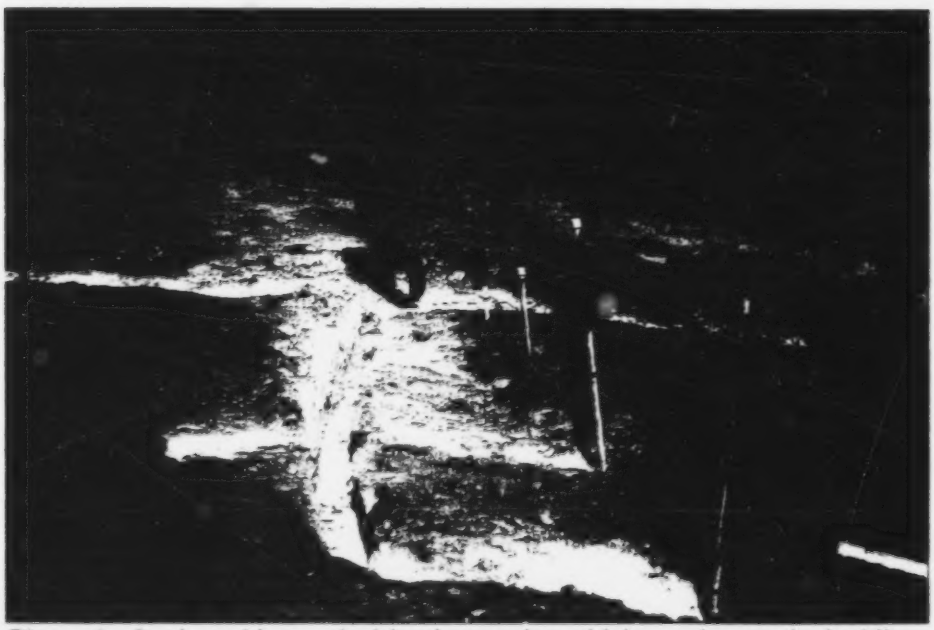

Photo 6 – Laying tubing and wiring in trenches with bentonite powder bedding.

Photo 7 – Water level reading at Research Site No. 9.

Photo 8 – Water sampling at Research Site No. 9.

Photo 9 – Field alkalinity testing.

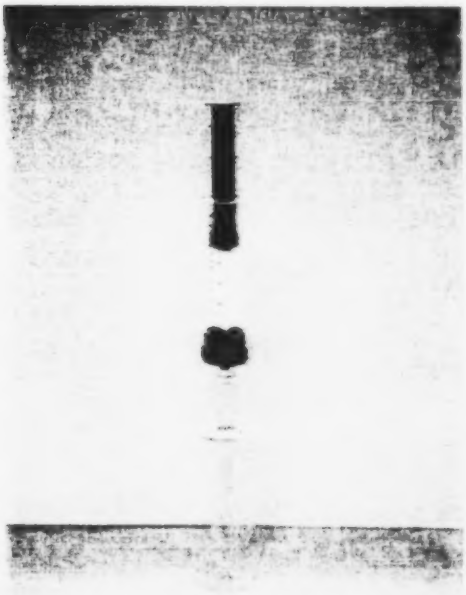

Photo 10 – Field filtering with 45 mm filter and syringe

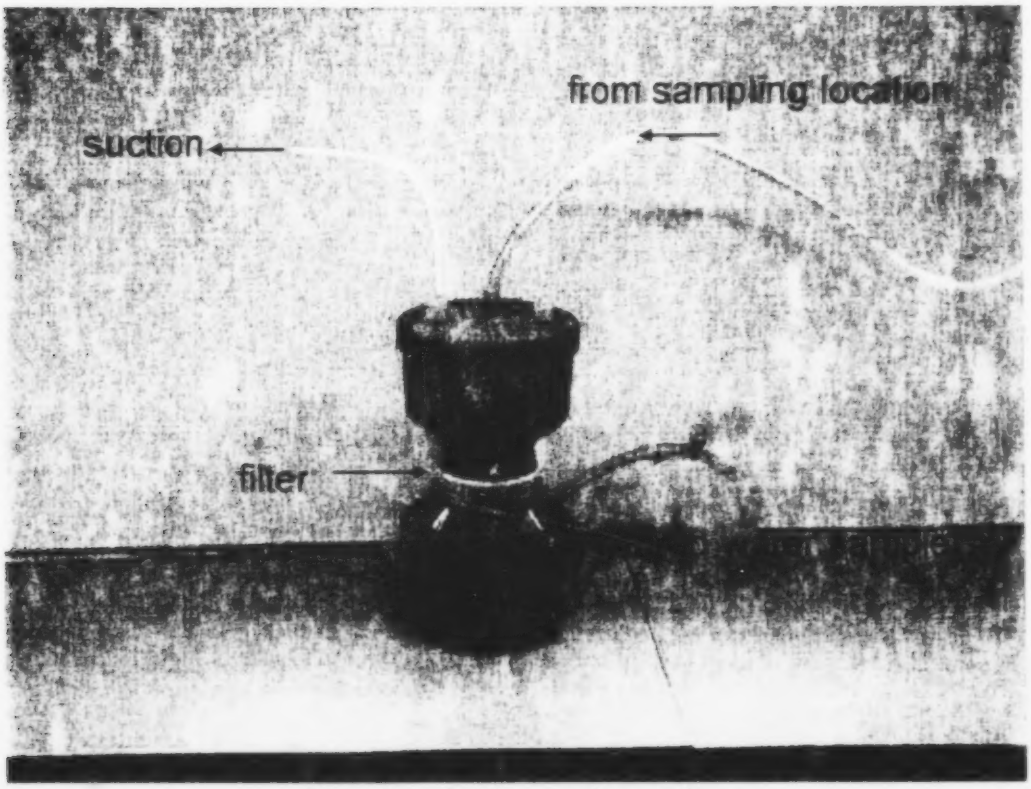

Photo 11 – Suction sample container.

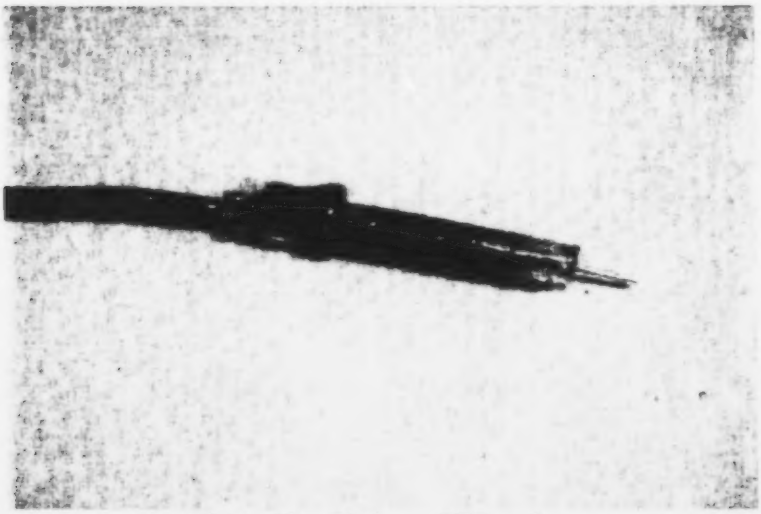

Photo 12 – Platinum ORP probe

Photo 13 – Sampling manure with depth from boat.

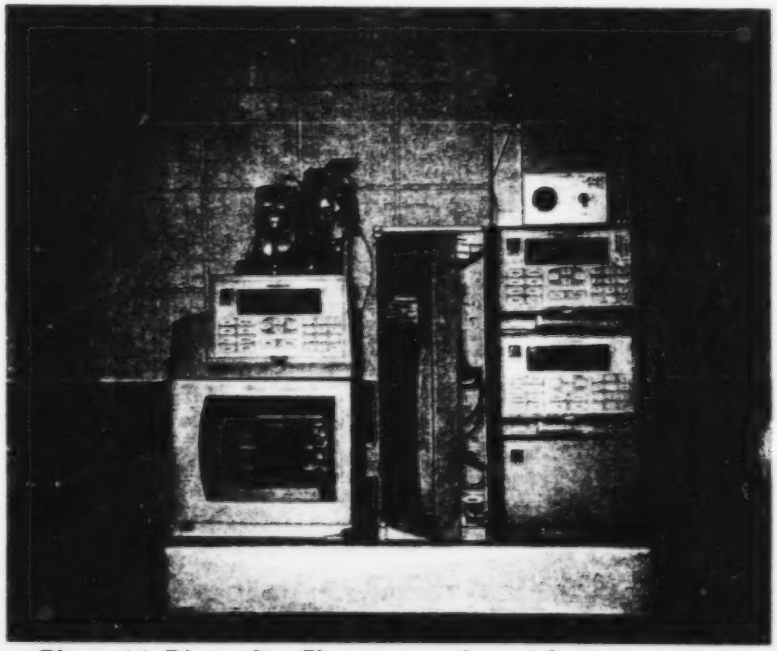

Photo 14- Dionex Ion Chromatograph used for water analysis

Photo 15 - Standpipe piezometre installation at Site No. 1

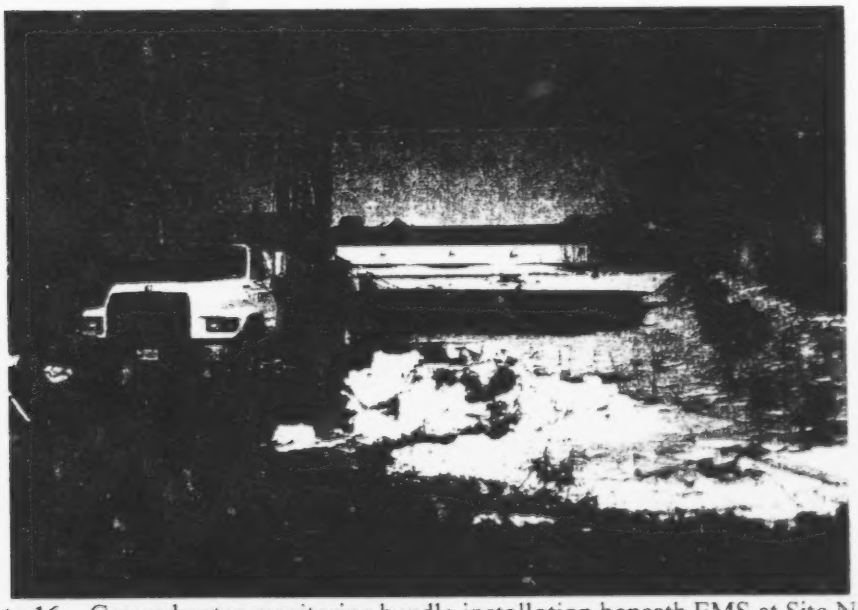

Photo 16 – Groundwater monitoring bundle installation beneath EMS at Site No. 1

Photo 17 - Groundwater monitoring bundle installation beneath EMS at Site No. 1.

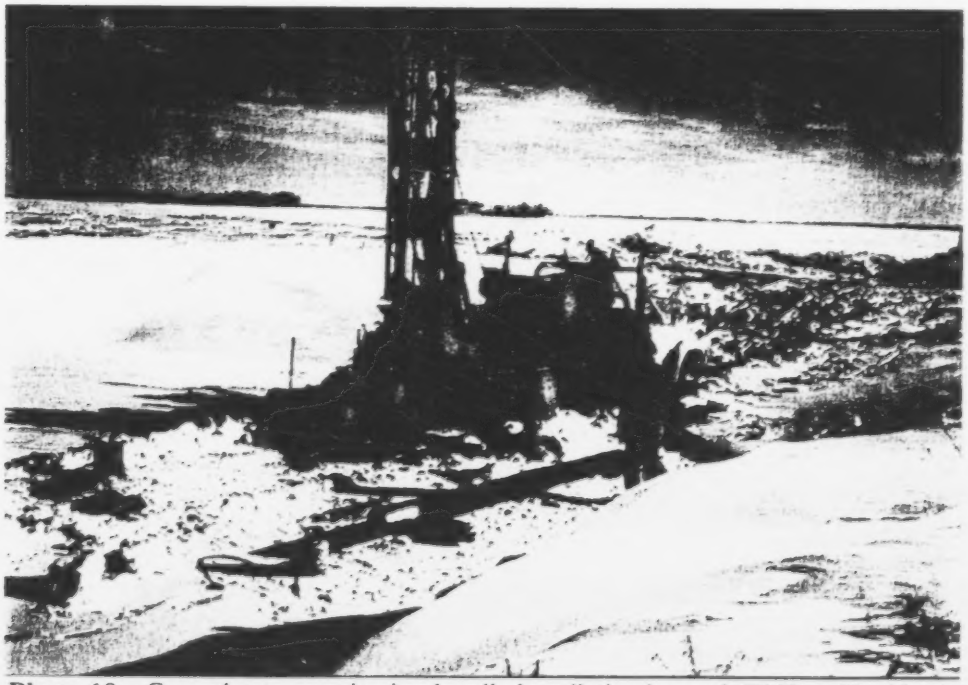

Photo 18 – Groundwater monitoring bundle installation beneath EMS at Site No. 1.

Photo 19 – Field analysis of groundwater samples at Site B.

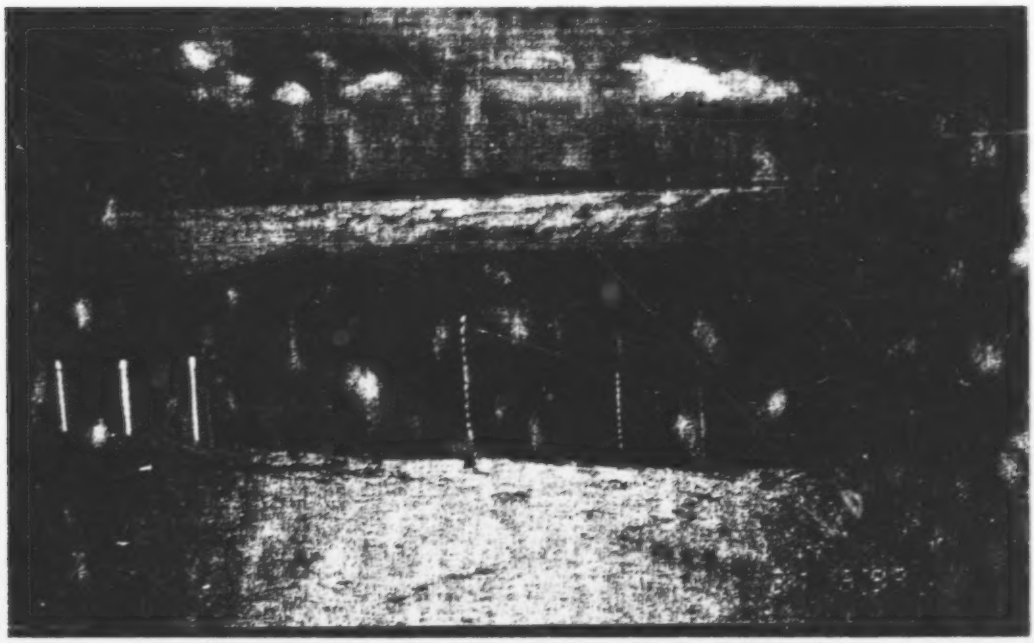

Photo 20 - Standpipe piezometres at Site B, Cell No. 2.